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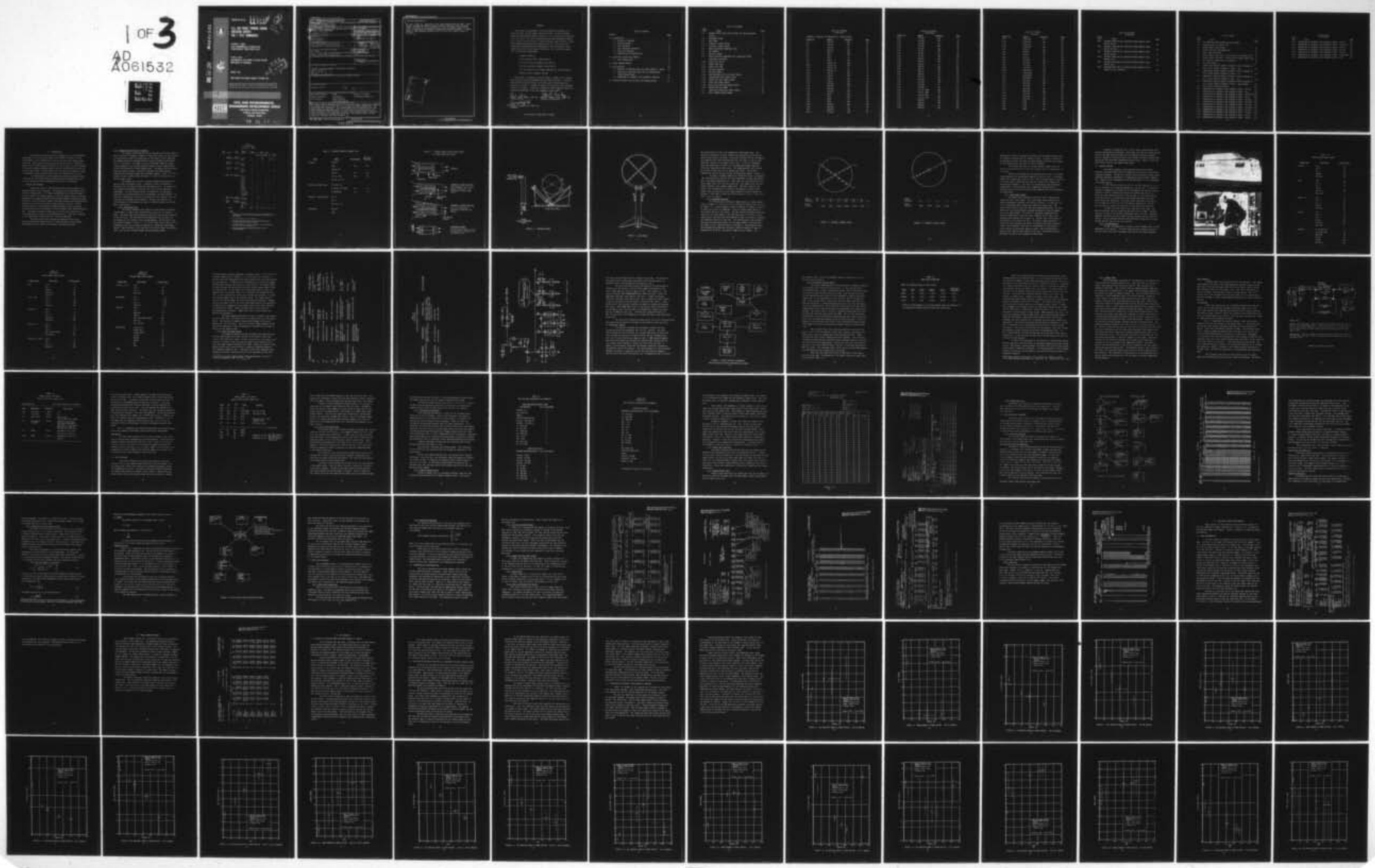

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U.S. AIR FORCE TURBINE ENGINE EMISSION SURVEY
VOL I TEST SUMMARIES

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DETACHMENT 1

AUGUST 1978

FINAL REPORT FOR PERIOD JANUARY 1975-JUNE 1978

Approved for public release; distribution unlimited

CEEDO

CIVIL AND ENVIRONMENTAL
ENGINEERING DEVELOPMENT OFFICE
(AIR FORCE SYSTEMS COMMAND)
TYNDALL AIR FORCE BASE
FLORIDA 32403

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The gaseous exhaust emissions from 14 military gas turbine engines were measured at various power levels from idle to full power including afterburning. SAE smoke number was determined. All measurements were made using the Air Force Mobile Emissions Laboratory which is a self-contained state-of-the-art gas turbine emissions test laboratory. Emission rates of hydrocarbons, carbon monoxide and oxides of nitrogen were calculated. The emission rate of sulfur oxides was estimated from fuel analyses.

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The body of data was analyzed to show relationships among the data. These studies included the effect of power setting on emission index and smoke number, variation of gas concentrations across the exhaust plume and the degree of uncertainty introduced by abbreviated sampling methods. A summary table of "Best Estimate" emission factors for all the engines tested is provided.

PREFACE

This report was prepared by Scott Environmental Technology, Inc. under Air Force Contract Number F29601-75-C-0046. The work reported herein was administered under the direction of the Environics Directorate of the Air Force Civil and Environmental Engineering Development Office (Det 1 ADTC) with Major Peter S. Daley serving as Project Officer. Work was performed from January 1975 through June 1977. The engine test program was performed with the cooperation of the following Air Force organizations and private engine overhaulers; their excellent cooperation is gratefully acknowledged.

Teledyne; Nesho MO

First Composite Wing; Andrews AFB MD

Air Force Logistics Command; Kelly AFB TX

Air Force Logistics Command; Tinker AFB OK

Air Force Tactical Air Command Headquarters; Langley AFB VA

General Electric Company; Lynn MA

This report is presented in three volumes. Volume I is an overall description of the work performed and the results obtained. A table of best estimate emission factors for Air Force gas turbine engines is presented in Volume I. Volume II contains the results of the individual tests of each engine. Volume III contains the Model Summaries which are statistical summaries of the test results by engine model.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES
(Continued)

FIGURES 4-1 THROUGH 4-84 EMISSIONS VS. POWER SETTING

LIST OF FIGURES
(Continued)

LIST OF FIGURES
(Continued)

LIST OF FIGURES
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LIST OF TABLES

LIST OF TABLES
(Continued)

1.0 INTRODUCTION

This report describes the work performed by Scott Environmental Technology, Inc. on Air Force Contract No. AF29601-75-C-0046. Before this program, little information existed on Air Force gas turbine engine emissions. These emissions data were necessary as inputs to dispersion models used for predicting the influence of the air base on the environment. The reported program provided baseline data on 19 different Air Force gas turbine engine types. Several engines of each type were measured in order to determine the most representative values of emissions for each type.

All measurements in this program were performed using the state-of-the-art Air Force Mobile Emission Laboratory which ranged from coast-to-coast during the 18 month measurement period of this program.

1.1 ENGINE TEST PROGRAM

During the course of this program 102 gas turbine engines were emissions tested at six locations. The engines tested represented current Air Force engine models. All exhaust measurements were made with sample probes located in the engine exhaust as near the exhaust plane as practical. The probes were remotely operated from the Mobile Emission Laboratory (MEL). The MEL is a state-of-the-art exhaust emissions analysis system specifically designed for Air Force gas turbine engine emissions testing. The MEL system includes all the analyzers, sampling probes and data recording systems necessary for the acquisition and recording of gas turbine emissions data. Emissions testing was conducted at Air Force and contractor test cell installations located in the continental U.S.A. Tests were conducted at all engine power levels from idle to full afterburning.

The data acquired were reduced and analyzed by Scott into emission indices and emission rates of carbon monoxide, total unburned hydrocarbons, nitric oxide, total oxides of nitrogen and smoke.

1.1.1 Engines Tested and Test Locations

The engines tested and their test locations are listed in Table 1-1. Also listed are the number of engines of each type tested, the test periods at each location along with tabulations of the types of tests conducted. The engines tested are standard military aircraft engines in wide use by the U. S. Air Force. The range in size is from small (1000 lb. thrust trainer engines) up to the most powerful fighter aircraft engines which utilize afterburning for thrust augmentation. The engines are distributed among four general types: turbojets, turbofans with mixed exhaust, turbofans with external exhaust and turboshaft engines. Table 1-2 lists the engines tested by exhaust type and Figure 1-1 depicts schematically the various engine types.

The engines were tested at several overhaul bases during their after-overhaul performance tests. In general it was not feasible to emissions test the engines during the performance tests. The engines were run through the performance tests and then re-run for the emissions measurement. At each overhaul center the possibility of running the emissions test simultaneously with the performance test was explored. In each case, simultaneous testing was discarded and the emissions tests were conducted on performance-tested engines. During a performance test, several engine trim adjustments are made to bring the engine into performance specification.

1.1.2 Probe Types Used

Two exhaust sampling probe types were used during the emission testing phase; a single point traverse probe, and a set of cruciform rakes. The single point traversing probe was the probe initially supplied by the Air Force. The rake probes were supplied by the Air Force for use during the later phases of the testing program. The two probe types are shown in Figures 1-2 and 1-3. The "single point" probe consists of an aerodynamic strut section which is mounted to a mechanical positioning system. Three nacelles, at the free end of the strut, house two sampling ports, one each for the smoke sample and gas analysis sample.

TABLE 1-1

AIR FORCE EMISSIONS

ENGINE AND TEST SUMMARY

Test Phase	Location	Test Dates	Engines Tested	Total No. Engines	Number of Tests: Cat A 13 pt.	Cat B 4 pt.	Cat B Rake	Cat C	Total No. Tests
2	Teledyne Neosho, Mo.	7 Mar 75- 15 Apr-75	J69-T25	11	1	10 (1)		1 (2)	12
			J85-5	10	1	9 (1)		2 (2)	12
3	Andrews A[illegible] Wash., D.C.	[illegible] Apr 75- 31 May 75	J60-P3	6	1	4		1	6
			J60-P5	5	1	4		1	6
4	Kelly AFB Texas	5 June 75- 7 Oct 75	J79-15	6	1	5		1	7
			T56-A7B	8	2	7		1	10
			TF39	4	4				4
6,7	Tinker AFB OK	10 Jan 76- 30 Apr 76	J75-17	2	1		3	1	5
			J75-19W	2			2		2
			TF33-P3	4	1		4	1	[illegible]
			TF33-P7	4	1		4	1	6
			TF41-A1	5	1		5	1	7
			TF30-P3	3	1		3	1	[illegible]
			TF30-P7	3	1		3		
			TF30-P100	4	1		4	1	
			J57-19W	3	1		3	1	
			J57-43 / J57-F43WB *	4	1		4	1	6
			J57-P21B	3	1		3	1	5
8	Langley AFB VA	13 June 76- 16 Aug 76	F100-PW100	5	2 (4)		5	1	8
9	GE-Lynn Mass.	28 Aug 76- 27 Sept 76	TF34(Dev.)	2	2				
			TF34(Prod.)	5	1	4		1	6
			T700	2	2				2
	TOTALS		20 (3)	102	28	43	43	19	133

NOTES

1) 2 Category B tests were performed at 5 power settings, remainder at three power settings - Idle, Norm, Mil. Additional power settings were two intermediates.

2) Non-standard smoke test done on J69 and J85.

3) J60-P3 and J60-P5 engines, and J57-43 and J57-F43WB engines were considered identical for emissions purposes.

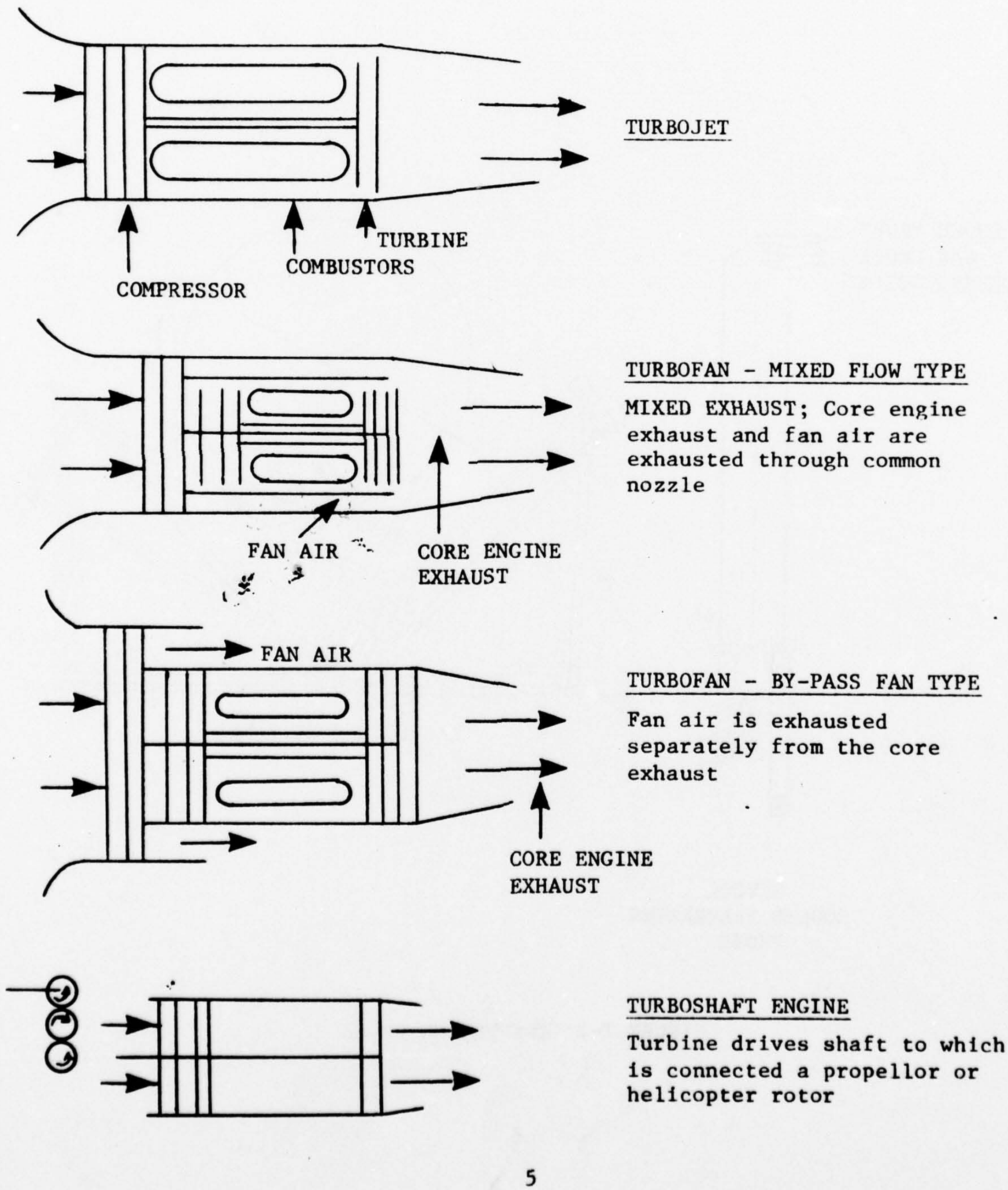
4) One regular category A test and one category A test performed during special test cell stack emissions tests.

* These engine models were grouped together because they have identical combustors.

TABLE 1-2 ENGINES TESTED BY EXHAUST TYPE

Type	Engine	Afterburner	A/B Test Performed
Turbojet	J69-T25		
	J85-5	Yes	Yes
	J60-P3, P5		
	J79-15	Yes	Yes
	J75-17, 19W	Yes	No
	J57-21, 43, 19		
Turbofan - Mixed Flow	TF 41-A1, A2		
	TF 30 P3, P7, P100	Yes	No
	F-100-PW100	Yes	No
Turbofan - External Fan	TF 39		
	TF 34		
	TF 33-P3, P7		
Turboshaft	T56-A73		
	T700		

FIGURE 1-1 TURBINE ENGINE TYPES TESTED DURING AIR FORCE EMISSIONS PROJECT



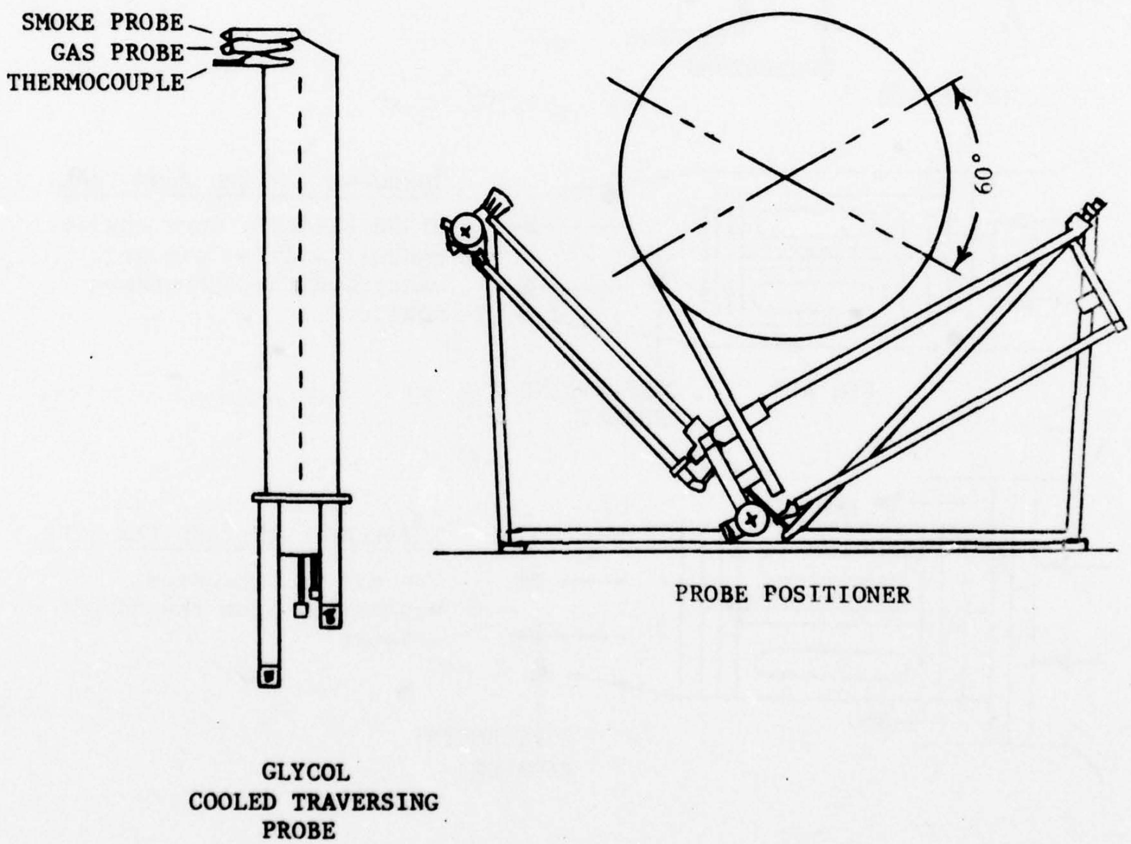


FIGURE 1-2 TRAVERSING PROBE

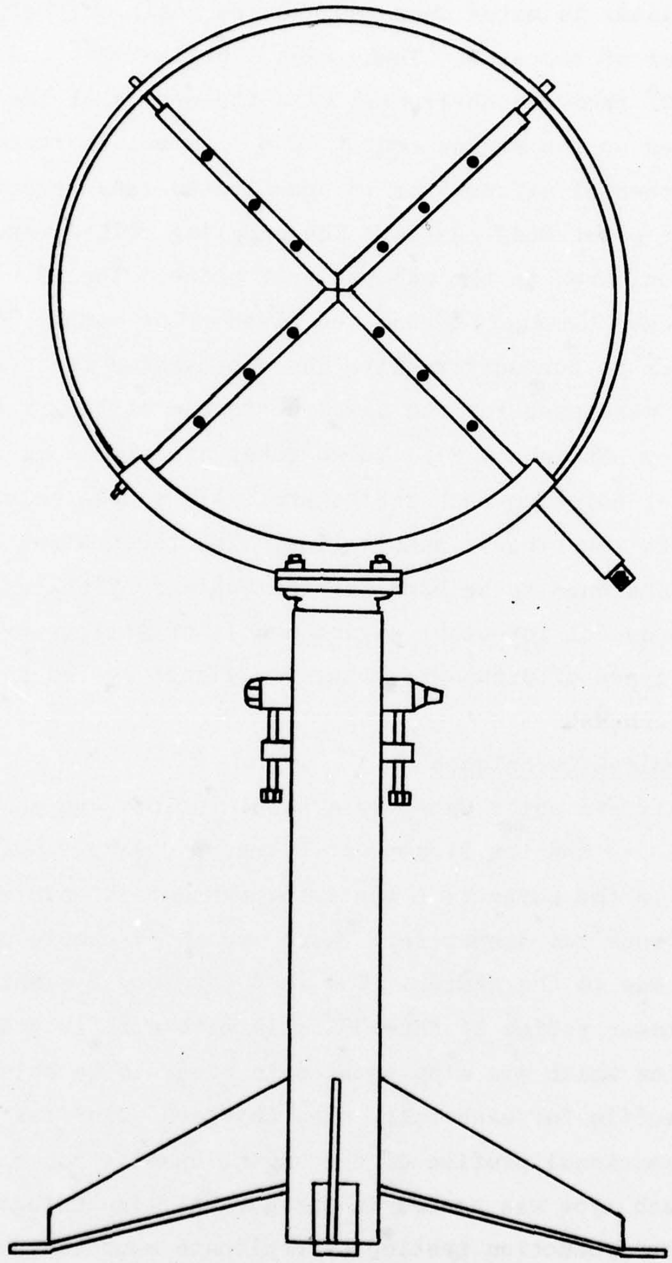


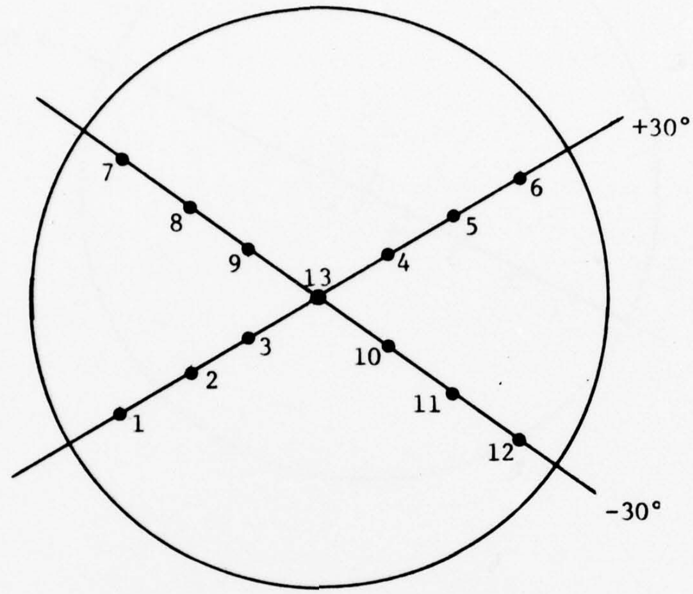
FIGURE 1-3 RAKE PROBE

The third nacelle is the total temperature thermocouple mount. The mechanical positioner is motor operated and can position the probe anywhere along either of two axes. These axes labelled +30° and -30 degrees are displaced ±30° from the horizontal with the center of the two axes typically centered on the engine center line. In use the traversing probe was positioned at either 5 or 13 preselected exhaust sampling points per engine power mode tested. The sampling points were located at centers of equal area in the exhaust exit plane. The 13 point sampling was defined "Category A" and the fixed point sample "Category B".

In order to further expedite the abbreviated tests of Category B the rake probes were used for the tests performed at Tinker AFB (phases 6 and 7) and Langley AFB (phase 8). These rakes are cruciform probes with three sample inlet holes on each radius arm. All sample holes are manifolded together to the exhaust sample line. The three sizes of rake probes were dimensioned to be used for the engines of phases 6 and 7 however they are useful for other engine models of similar exhaust exit diameter. Both types of probe were ethylene glycol cooled to remove the heat of the jet exhaust.

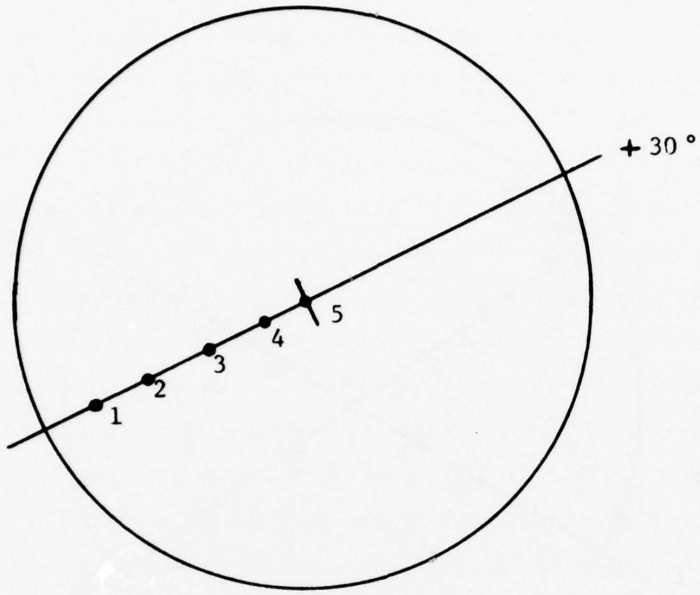
1.1.3 Sampling Techniques

The thirteen point Category A sample points are shown schematically in Figure 1-4 and the five point Category B sample points are shown in Figure 1-5. In the Category A tests the exhaust is sampled at centers of equal area across two diameters. There are three sample points on each radius and one in the center. The four Category B sample points are located on the lower radius of the +30° axis with a fifth point on the engine center line which was also sampled in order to be able to construct the emissions profile for each test. The thirteen point test provides a detailed cross-sectional profile of the engine exhaust concentrations. One engine of each type was tested in Category A. The Category B tests were designed for production testing of replicate samples in order to expeditiously build up a statistical number of test engines. The



Sample Point No.							
+30°	1	2	3	4	5	6	
-30°	7	8	9	10	11	12	13
Sample Position	-.913R	-.707R	-.408R	+.408R	+.707R	+.913R	0

FIGURE 1-4 CATEGORY A SAMPLE POINTS



Sample Point No.	1	2	3	4	5
Sample Position	-.935R	-.790R	-.612R	-.354R	0

FIGURE 1-5 CATEGORY B SAMPLE POINTS

abbreviated testing of Category B required much less engine running time for emissions testing than the Category A tests. Category A tests were accomplished in about two hours of engine running time while the Category B tests required about one hour and fifteen minutes.

The exhaust mass flow at each gas analysis sample point was computed from measurements of the total pressure and total temperature at each point.

Exhaust total temperature was measured with either the rhodium, iridium/rhodium (IR) thermocouple supplied by the Air Force or a Chromel-Alumel (CA) thermocouple built by Scott. The IR thermocouple is housed in a zirconia ceramic shield and was used for testing those engines with afterburning capability. For tests not requiring the high temperature thermocouple, a Chromel-Alumel total temperature thermocouple in a stainless steel shield was utilized saving needless wear on the expensive IR thermocouple.

1.1.4 Power Modes Tested

The engines were emissions tested over their complete power range from idle to full power. The actual power levels used were the same as performance testing levels wherever possible. In addition, one or two intermediate power levels were added for completeness. All engines were tested at idle and full (non-afterburning) power. The full power level is called military, maximum continuous or take-off depending on the engine model. The lack of a consistent nomenclature for military engine power levels can cause confusion to the user of the emissions data presented in Section 1.6. The per cent of full power or rated power is included in the data. In order to apply the data to actual aircraft operations the power level used in each mode (take-off, climb, cruise, approach, taxi) must be ascertained for each aircraft type in which the particular engine is used. Then the appropriate emission level from the data tables can be used. Interpolation may be necessary for some of the intermediate power modes.

Category A testing was done at Idle, Normal (approximately 90%), Military and Maximum Afterburning. These power settings were chosen because they are the same power settings used in acceptance testing overhauled engines. Category B tests were run at Idle, Normal, Military, Maximum Afterburning and two additional Intermediate Power Levels. Table 1-3 lists the power levels used for each engine type tested.

1.2 ANALYSIS SYSTEM

The exhaust analysis system used was the Air Force Mobile Emissions Laboratory (MEL) which was supplied to the project as government furnished equipment. The MEL is a state-of-the-art aircraft turbine engine emissions laboratory contained in a converted Air Force patient transport bus. Figure 1-6 is a photograph of the MEL and Figure 1-7 is a photograph of the MEL interior.

The MEL analytical system is built to the EPA standards of July 17, 1973 as published in the Federal Register Vol. 35, No. 136. A controlled laboratory atmosphere is provided for the instrumentation and the operators through a carefully designed heating and air conditioning system. An excellent sound absorbtion shield allows the MEL to be operated adjacent to an open air jet test stand while maintaining comfortable listening levels within the laboratory. Electrical power requirements are 440 V ac, 3ϕ at 50 Amperes or 220 V ac 3ϕ at 100 Amperes. Additionally, 109 gpm cooling water is required for the glycol cooled probe heat exchanger.

The MEL is 55 feet long, 8 feet wide and 13 feet high. The emission analyzer consoles occupy the main section of the MEL. Cylinder racks are located in the driver's compartment and in the rear. Permanent plumbing connections are used between the gas cylinders and the operators console. A self contained intercom system provides communication between the MEL operator and the test cell operator.

1.2.1 Instrumentation

The MEL instrumentation is housed in four equipment bays located lengthwise in the vehicle. Its three operators have convenient access to the three main areas; data recording, probe control and smoke sampling.

FIGURE 1-6 MOBILE EMISSIONS LABORATORY (MEL)

FIGURE 1-7 MEL INTERIOR

TABLE 1-3

ENGINE POWER LEVELS TESTED

Engine Type	Power Mode	% Rated Power
J69-T25	Idle	38
	Int. 1	45
	Int. 2	75
	Normal	84
	Military	100
J85-5	Idle	46
	Int. 1	65
	Int. 2	87
	Normal	92
	Military	100
	Max. A/B	--
J60-P3. P5	Idle	43
	Int. 1	75
	Int. 2	85
	Normal	97
	Military	100
J79-15	Idle	65
	Int. 1	75
	Int. 2	93
	Normal	89
	Military	100
	Max. A/B	--
T56-A7B	Lo Ground Idle	3
	Hi Ground Idle	8
	Approach	18
	Cruise	72
	Normal	100
	Military	109

TABLE 1-3
(Continued)

ENGINE POWER LEVELS TESTED

Engine Type	Power Mode	% Rated Power
TF39	Idle	6
	Int. 1	75
	Normal	97
	Military	100
	Take Off	104
J75-17, 19W	Idle	6
	Int. 1	68
	Int. 2	88
	Military	100
TF33-P3, P7	Idle	5
	Int. 1	75
	Int. 2	85
	Military	100
	Take Off	105
TF41-A1, A2	Idle	5
	Int. 1	65
	Int. 2	72
	Mid. Cruise Power	85
	Full Power	100
TF30-P3, P7, P100	Idle	5
	Int. 1	75
	Int. 2	85
	Military	100

TABLE 1-3
(Continued)

ENGINE POWER LEVELS TESTED

Engine Type	Power Mode	% Rated Power
J57-19W, 21, 43	Idle	5
	Int. 1	75
	Int. 2	85
	Military	100
F100-PW100	Idle	2.1*
	Int. 1	2.3*
	Int. 2	2.9*
	Military	3.7*
TF34-100	Idle	7
	Int. 1	12
	Approach	34
	Cruise	59
	Max. Continuous Power	100
	Take Off	125
	Max. Redline	130
T700-GE-700	Ground Idle	2
	Flight Idle	14
	Ground Idle +	6
	25% MC	20
	50% MC	40
	75% MC	60
	MC	75
	IRP	90

*EPR

The main exhaust analysis equipment is listed in Table 1-4 and the system is shown schematically in Figure 1-8. The analyzers are arranged in parallel bays with independent electrically operated zero and span controls for each analyzer. In addition, all instruments can be zeroed or spanned simultaneously through the electrical control system. The exhaust sample is driven through the analyzers by two metal bellows sample pumps located in a heated oven. The two pumps can be connected either in series for pumping from a low pressure source or in parallel for doubling the flow rate. In the reported test series only one pump was necessary to provide the required sample flow to the analysis system. All sample lines in contact with the gas sample are heated and thermally insulated. Temperatures of the sample line to the total hydrocarbon analyzer are maintained at $300^{\circ}F$ and the temperature of the sample lines to the other analyzers are maintained at $150^{\circ}F$. Heated capillary ovens are used on both chemiluminescence analyzers. Sample flow rates to each analyzer are metered and adjustable.

The smoke sampling instrument is built according to the specifications of ARP 1179.* The active area of the smoke filter is 1.453 square inches. The quantity of exhaust volume pulled through the filter is measured by a wet test meter. The wet test meter sample temperature and pressure are measured so that the appropriate corrections can be made to obtain the true sample volume.

1.2.2 Data Recording System

As originally supplied the MEL instrument data along with the various system temperatures were recorded on the printed ticker tape output of Kaye 8000 data logger. Manually recorded were the exhaust total pressure, instrument ranges and mode and sample point identifications. These were hand logged on suitable data forms. During the course of this program the MEL was retrofitted with a completely automated system of data logging on magnetic tape. This made the data more compatible with computer processing, removing the need for key punching the data from

* "Aircraft Gas Turbine Engine Exhaust Smoke Measurement", Society of Automotive Engineers, ARP 1179, May 4, 1970

TABLE 1-4

EXHAUST ANALYSIS INSTRUMENTATION

Parameter Measured	Sensing Method	Instrument Type	Full-Scale Ranges
C_xH_y	Flame Ionization	Beckman 402	5 to 250,000 ppm C in 8 steps
CO	Nondispersive Infra-Red	Beckman 864 Beckman 864	100, 300, 1000 ppmv 1000, 3000, 7000 ppmv
CO_2	Nondispersive Infra-Red	Beckman 864	5, 10, 20 percent
NO	Chemiluminescence	TECO 10B	2.5 to 10,000 ppmv in 8 steps
NO_x	Chemiluminescence	TECO 10B with converter	2.5 to 10,000 ppmv in 8 steps
Smoke	SAE Smoke Number as per ARP 1179	Filter Reflectometer	---
Exhaust Total Temperature	Thermocouple in Total Temperature shielded housing	Iridium-Rhodium/Iridium T/C or Chromel-Alumel T/C	Up to 3000^{o} F Up to 2000^{o} F
Exhaust Total Pressure	Exhaust sample probe	Setra Systems Model 204 Pressure Transducer	0-50 psia
Ambient Temperature and Humidity	Platinum Thermometer and Sulfonated polystyrene ion exchange humidity sensor	General Eastern Model 400C	-50 to + 150^{o} F 0-100% R.H.

TABLE 1-4
(Continued)

EXHAUST ANALYSIS INSTRUMENTATION

Parameter Measured	Sensing Method	Instrument Type	Full-Scale Ranges
Data Acquisition System	Computer Operated Magnetic Tape Recorder	Wang Model 2200 S Computer with Wang Model 2201 Output Writer and Wang Model 2209 9-track Tape Drive	
Instrument Range/Mode	I/O for Wang System	Fluidyne 7200	
Data Logger and T/C Conditioner	A/D Conversion	Kaye Model 8000	

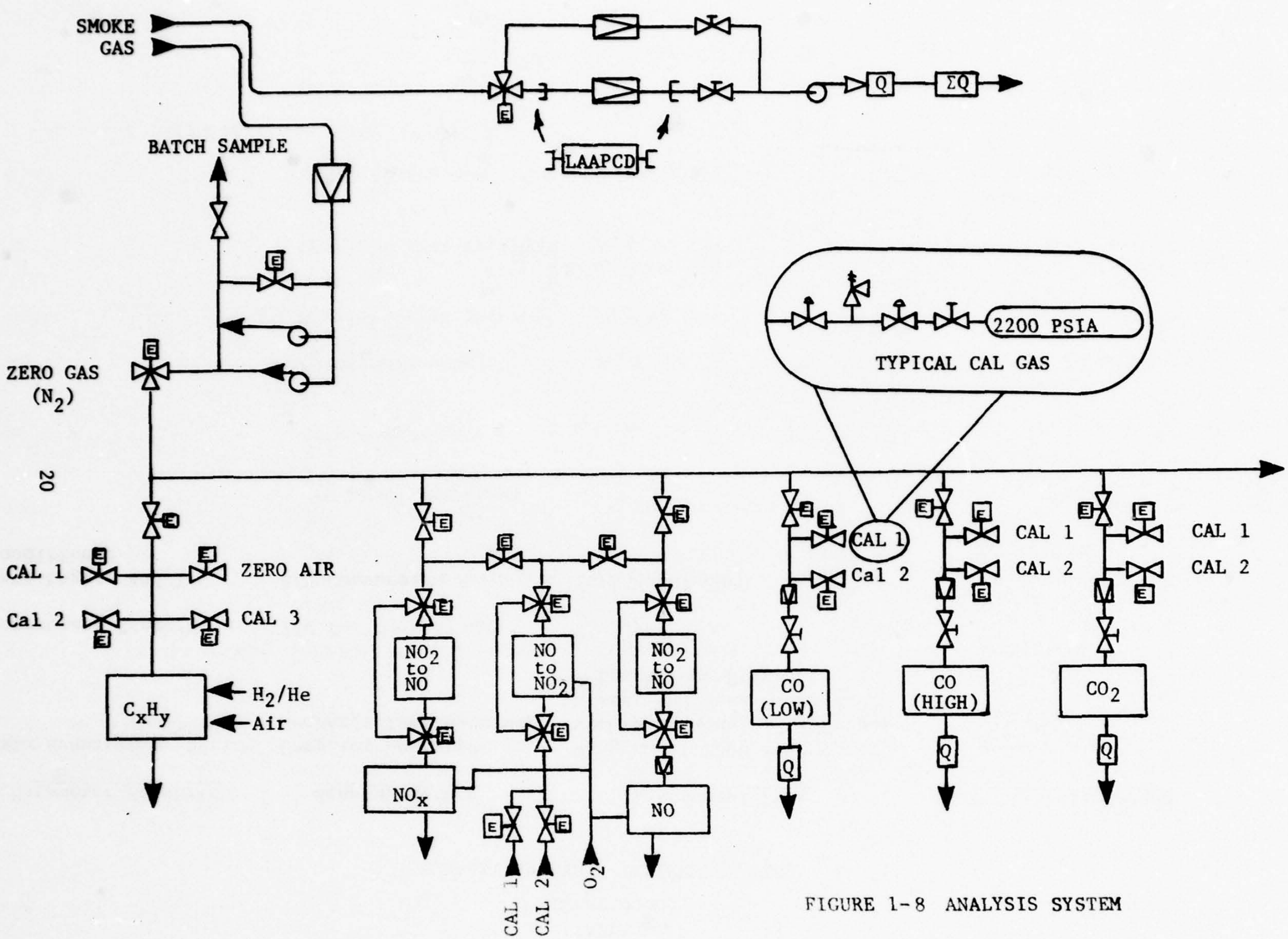


FIGURE 1-8 ANALYSIS SYSTEM

the ticker tape and hand logs onto computer punch cards. The details of the improved data acquisitions system which were developed under the reported contract are documented in References 2 and 3.

The data processing software developed for the MEL provided a capability to the system to record turbine engine environmental test data on IBM computer compatible magnetic tape. (See Figure 1-9). The system utilized a WANG LABORATORIES Model 2200T processor to drive the WANG Model 2209 Nine Track Magnetic Tape Unit. A model 2201 Output Typewriter provided a hard copy output, while an immediate visual display of data was provided on the processor's Cathod Ray Tube (CRT). A tape cassette unit and a keyboard provided the means for program and operator data entry. Three WANG Model 2250 I/O Controllers allowed the system to accept digital data from both KAYE and FLUIDYNE data loggers and output data to the Magnetic Tape unit. The KAYE unit scanned 30 Channels of MEL test data while the FLUIDYNE unit provided instrument range and system status data.

The system was integrated through direct electrical interconnections and system control placed in the hands of the operator by his selection of programmed commands.

Four distinct programs were developed to operate the data acquisition system and subsequent tape printout feature. The first three programs were tied together in a program "Executive" to allow data entry through the keyboard, the KAYE interface and the FLUIDYNE interface and to record this data on magnetic tape. A WANG-supplied Magnetic Tape Utilities Program was substantially modified and incorporated into the software design andused to operate the nine track tape unit. A number of system status checks and "Tape-Ready" checks were provided in the system to assist the operator. The fourth program is a unique program designed to produce a typewriter copy of the data stored on magnetic tape for use in the event the tape was lost or damaged and also to provide

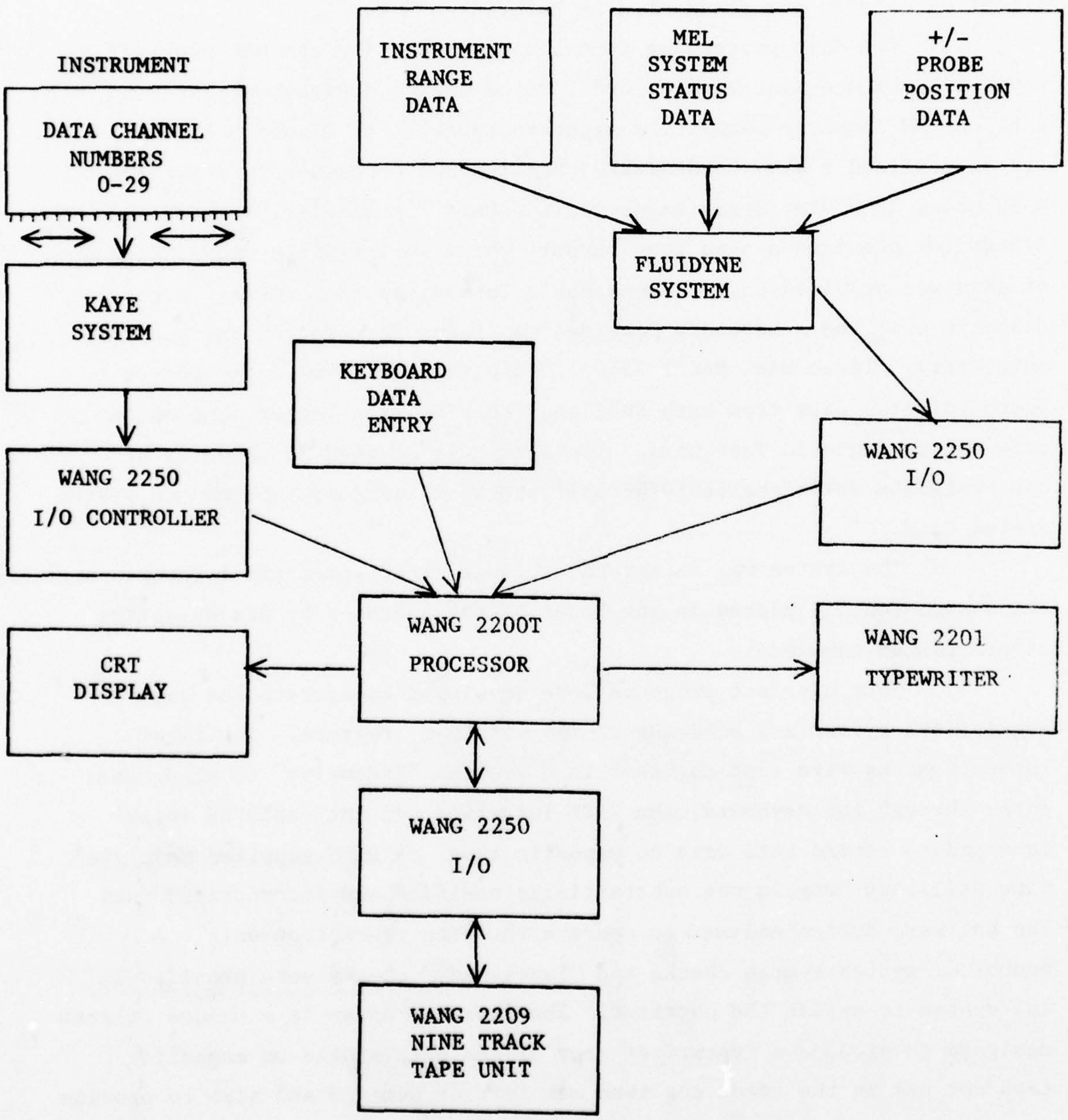


FIGURE 1-9 MOBILE EMISSION LABORATORY

DATA ACQUISITION SYSTEM FUNCTIONAL FLOW CHART

the operator with a record of instrument operation during the test for quality control purposes.

1.2.3 Probes and Coolant System

The exhaust sampling probe (traversing probe) originally supplied to the project was constructed of mild steel. It was ethylene glycol cooled/heated with a coolant conditioning system. Before testing the probe was heated to 150°C through the glycol system. When testing the glycol coolant temperature was cooled by a heat exchanger to maintain the 150°C temperature. At the beginning of field testing of Phase 2 in February 1975, a second probe made of high nickel steel was under fabrication at AEDC for this project. During afterburning tests on the first J85 engine using the original probe a crack developed in the probe outer skin and the leading edge of the probe and the probe tip showed red color during afterburning. The Project Officer elected to suspend afterburning tests until receiving the new high nickel probe from AEDC. The last two J85 engines measured were tested in maximum afterburning using the original mild steel probe since the high nickel probe had not yet been delivered. It was not possible to keep the mild steel probe in the afterburning exhaust stream long enough to stabilize the emissions analyzers before the probe showed color.

The new high nickel steel probe was delivered in time for the Phase 4 tests of the J79 engines at Kelly AFB. However, this probe also showed color along the leading edge during afterburning tests. AEDC verified that this could be expected and was acceptable. Five J79 tests including afterburning were performed without incident except for the failure of one of the IR thermocouples. On the sixth J79 test, the new probe was bent at the probe flange during an A/B run. It was then sent back to AEDC for repair. The remaining tests at Kelly on the T56 and TF39 engines were performed with the original mild steel probe.

Three new rake probes were built by AEDC prior to the engine tests at Tinker AFB. The dimensions of the small, medium and large rakes are detailed in Table 1-5.

TABLE 1-5

RAKE PROBE DIMENSIONS

Radii for Sampling Points of Rake Probes.

Rake	Code	Inner	Middle	Outer	Effective* Hoop Dia.
Small	RS	3.125	7.375	9.50	30.5
Medium	RM	3.375	8.875	11.625	35.3
Large	RL	5.25	12.625	16.50	45.0

* Effective Hoop Diameter is the hoop diameter minus the dimension of the manifold box which projects inside the actual hoop.

These rake probes were glycol cooled by the same coolant conditioning system as the traverse probe. Due to the large exposed area of the rake probes as compared to the traversing probe and the greater heat flux to the rakes, it was not possible to use these rakes for A/B tests. A modified test schedule was devised by the contract officer to minimize the impact of the emissions test on the Tinker test cell schedule. The rake probes were used for all the Category B tests effectively decreasing the test cell time required. The medium rake developed hairline cracks in the outer skin between the sample ports. Repairs were made by the Tinker shops. The repaired high nickel probe failed by a rupture along the probe leading edge during the sampling of the first J75 engine. The Tinker tests were completed using the repaired rake and the original traverse probe. A larger heat exchanger was purchased by Scott to AEDC specifications before commencing the F100 tests at Langley AFB. During the week of July 19, tests were conducted on the new glycol cooling system. AEDC supervised the tests. The tests were conducted using the high nickel steel traversing probe mounted behind an F100 engine. AEDC calculations indicated that the new heat exchanger was still insufficient to withstand the anticipated 3900^{o}R total temperature. The glycol-cooled probe maximum working temperature is 3500^{o}R due to limitations in the thermodynamics of cooling by nucleate boiling with glycol. The probe tests verified the calculations. The probe cooling was adequate at power settings up through full unaugmented power. In Zone 2 afterburning, the probe leading edge below the thermocouple nacelle showed color. It was therefore decided that no afterburning tests would be conducted on F100 engines.

In short, the measurement of the emissions of afterburning engines, was only partially achieved because of inadequate sampling probe and cooling system. This failure occurred because the state-of-the-art of probe testing in afterburner streams was inadequate. The knowledge gained in this program, however, led directly to the design of a successful afterburner probe in a subsequent program.*

*F100 Engine Emission Test Report, USAF Contract No. F08635-77-C-0216, Scott Environmental Technology, Inc. Report No. SET 1628-01-0177, Oct. 1977.

1.2.4 Sample Lines

The heated sample lines used for the majority of the project were those provided by Technical Heaters, Inc. These were 100 foot 3/8 inch Teflon lines insulated and electrically heated. They operated with a minimum of difficulty. One of these lines was damaged during a TF39 test and repaired by the manufacturer. The sample lines originally supplied to the project were made by Thermal Systems, Inc. Several failures with these lines led to their abandonment early in the field testing. During the period before receiving the Technical Heaters lines, heated 3/8 inch diameter stainless steel lines supplied by Scott were used. These Scott lines were originally designed and built for the EPA gas turbine emissions variability study. A minor operational difficulty with these stainless steel lines was discovered while emissions testing T56 engines. Conversion of NO_2 to NO was apparently taking place in the heated stainless steel lines. A special test using a T56 engine was conducted to evaluate this problem. A recently delivered Technical Heaters line and the Scott stainless steel line were connected between the sample probe and the MEL. Either line could be selected by the MEL operator through a system of solenoid valves. The emissions analyzers indicated the same levels of all emissions species except NO. The NO_x levels were the same but the relative amount of NO was different. Tests were conducted on the two lines while waiting for TF39 engine tests. The differences noted earlier were confirmed using mixtures of NO in air and NO plus NO_2 in air. The total NO_x levels were the same when the lines were heated and broken-in. NO_x was conserved in both lines. Conversion of NO_2 to NO occurred in the stainless steel sample line probably due to catalytic action at the sample line temperature (300^oF). This effect had not been observed before in this writer's experience with gas turbine testing but may have been present. The important thing is that no NO_x has been lost in the previous tests and only the ratio of NO to NO_x may have been affected. The following is a description of the experimental set-up used to explore the differences in the two sample lines when sampling NO and NO_2 mixtures.

Test Procedure

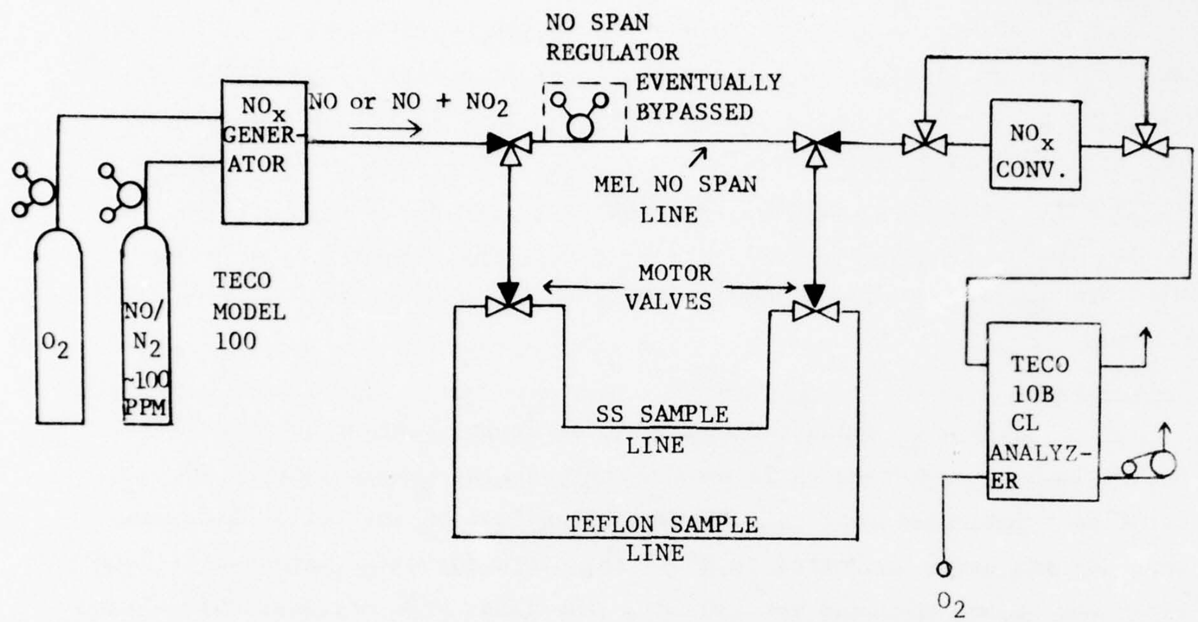
A NO/NO_x sample was synthesized in the NO_x generator. This sample could either go directly to the chemiluminescent analyzer through the MEL span line or be routed through either the 100 foot Teflon line or the 60 foot stainless steel line (see Figure 1-10). The levels involved at the source were about 70-80 ppm NO_x of which 20-30 ppm was NO. After the initial tests, the stainless steel line was washed out with acetone and a wiper run through to loosen up the lampblack followed by a final flush with acetone.

Test Results

Tests were conducted to try to determine whether NO or NO_2 was either lost or converted while passing through the sample lines. The first test indicated that some NO_2 was being lost on the teflon lines and that NO_2 was being converted to NO in the stainless steel lines while both lines were being operated hot (300°F). The lines were operated over a range of temperatures between ambient and 300°F.

Table 1-6 summarizes the results obtained in the initial tests using the lines as used during the T56 engine tests, i.e. the Teflon line was new and clean and the stainless steel line was soot-coated on the inside. Both lines absorbed NO_x (probably the NO_2). The stainless steel line at ambient temperature absorbed 45% of the NO_x and the Teflon line heated to 300°F absorbed 13% of the NO_x in the first test. The dirty cold stainless steel line also absorbed NO_2. After heating to 300°F the hot stainless steel line (still dirty) absorbed none of the NO_2. As the stainless steel line temperature increased, more and more NO_2 was converted. The cold stainless steel line (dirty) on a second trial absorbed 1/3 of the NO_x. When reheated to 300°F, it showed no loss of NO_x and again conversion of the NO_2 to NO. At 300°F the conversion of the NO_2 present was essentially 100%.

The stainless steel line was then cleaned to see if the NO_2 absorption experienced with the cold line could be eliminated. The Teflon



Sample Line

SS Line - 60 feet long - same line used for J79 and T56 tests Kelly AFB, Texas, June through August 1975. Made up of 2 sections 3/8 O.D. x .049 wall SS type 304 20' long and 1 section 3/8 O.D. x .035 wall SS line. The stainless steel line was coated with soot (carbon black) from the engine tests.

Teflon Line - 100 foot length of Technical Heaters Teflon line 3/8" O.D. TFE tube with .035 wall. This line was brand new and had never been used on engine tests.

FIGURE 1-10 NO/NO_x TEST SET-UP

TABLE 1-6

NO/NO_x SAMPLE LINE TESTS

RESULTS WITH DIRTY SAMPLE LINE

NO_x Absorption — All Test Flow Rates ∿1.75 SCFH

Line	Temperature	Condition	Loss % NO_x
TEF	Hot 300°F	Clean	13
SS	Cold 95°F	Dirty	45
SS	Warm 150°F	Dirty	Gain of NO_x 31% increase over input!
SS	Warming Up To 300°F	Dirty	Amount of Excess NO_x Over Input Decreases With Time ∿1 Hr. During Heating Until NO_x In = NO_x Out on the SS line
SS	300°F	Dirty	Negligible to no loss after ∿3 Hr. Period
TEF	300°F	Clean	Negligible After ∿3 Hr. Period

line was also tried cold. A small amount of the NO_2 (4%) was absorbed by the cold Teflon line. The cleaned stainless steel (cold) line showed 6% loss of the NO_x. It should be noted that this was about the level of uncertainty in the NO/NO_x line test system at this point. There were system flow problems which affected instrument accuracy which was not resolved until later in the tests. The flow problem was caused by the span system pressure regulator. The sample line test system was improved by removing the regulator in the span line (DIRECT). The NO_x loss measured with the stainless steel sample line at $300^{\circ}F$ was now zero. However, the NO_2 to NO conversion was still approximately 100%. Therefore, it can be concluded that the lampblack coating absorbed NO_2, and that catalytic conversion of NO_2 to NO probably occurred at the heated stainless steel walls.

Table 1-7 summarizes the results obtained with the cleaned stainless steel line compared to the Teflon lines and the direct measurement.

Conclusions

No loss of NO_x occured in the two types of sample lines (stainless or Teflon) used in measuring gas turbine emissions. New Teflon lines undergo a break-in period where some NO_2 is lost. However, this period is quite short on the order of a few minutes of exhaust sampling time. Conversion of NO_2 to NO does occur in heated ($300^{\circ}F$) stainless steel lines probably by catalysis; however, the total NO_x sample was conserved even in stainless steel lines internally coated with soot.

1.3 TEST PROCEDURE

This section describes the general procedure for emissions testing Air Force gas turbine engines during the reported program. All the engines were tested after regular post-overhaul performance run-ups in instrumented test cells. Specially constructed brackets positioned the sample probes behind the engine exhaust nozzles. Sample lines and probe control cables were passed through the test cell walls to connect

TABLE 1-7

NO/NO_x SAMPLE LINE TESTS

RESULTS WITH CLEANED SAMPLE LINE

Mode	NO	NO_x	Temp.	Remarks	
DIR	53	79.5	Cold		
TEF	28.5	76	Cold $100^{\circ}F$	4% Loss of NO_x	
SS	43.5	53	Cold $100^{\circ}F$	33% Loss of NO_x	
DIR	50	80	Cold		
DIR	50	80	Cold	Repeated after 2 min. elapsed time	
SS	37	54	Cold	32% Loss of NO_x	
					Heat Lines
SS	82	82	$300^{\circ}F$		
TEF	34	82	$300^{\circ}F$		
DIR	81	82	Cold	Generator O_3 Off	All same indicate NO_2 absorption by TEF has reached Saturation
DIR		82		Generator O_3 On	

into the MEL which was parked adjacent to the test cell outer wall. The engines were performance tested first and then emissions tested. Emissions tests were made at several engine power settings from idle to full power.

Category A tests documented 13 sample points, 12 at centers of equal area on two exhaust plane diameters plus the center. Category B tests were done by either sampling at four centers of equal area on one nozzle radius or by sampling with a rake probe of 12 sample points manifolded together. Once the test engine was stabilized at a given power setting, the emissions readings were taken at each of the exhaust sample points. The engine operating conditions were logged by the test cell operators at the beginning and end of the emissions measurements at each power setting.

1.3.1 Test Cell Installation

The exhaust sample probe stands and support equipment were attached either to the test cell floor or to the augmenter supports or both. Each test cell installation was different. In most test cells the traversing probe positioner could be mounted directly to the floor by first bolting down steel plates to the cell floor with concrete anchor bolts. Pads pre-drilled and threaded were then welded to the steel plates. The flat flanges of the probe positioner were then bolted down to the steel pads using the appropriate shims as necessary to align the traversing probe to the engine centerline.

For those test cells with elevated engine mounts such as those experienced at Tinker, Kelly and GE-Lynn, trusswork stands were built upon which the probe positioner was mounted. The rake probe was mounted in the same fashion as the movable probe.

The glycol coolant system was located in the test cell adjacent to the sample probe. Test cell water lines were connected to the water cooled heat exchanger. Flexible lines connected the coolant system to the probe allowing the probe freedom of movement. Control cables for the coolant system and the smoke and gas sample lines were passed through

access ports in the test cell wall. The probe positioner, coolant system and sample line heaters were all remotely operated from the MEL.

The MEL was operated from either 440 V ac or 220 V ac, 3ϕ power. The MEL intercom system was connected to the test cell to allow direct communications between the MEL operator and the test cell operator.

1.3.2 Calibration Procedures

When beginning operations at a new site the instruments were warmed up as soon as possible. After initial checkouts for damage or improper operation, the analyzers were zero balanced. A complete calibration was then performed on each instrument. Table 1-8 lists the calibration and span gas inventory used for these calibrations. If in comparing the calibration results with previous calibrations a discrepancy was noted, then the source of the discrepancy was ascertained and remedied. Calibration gases which had apparently changed concentration since their last analysis were sent to Scott, Plumsteadville for re-analysis. Sometimes, glass flask samples were collected from questionable calibration cylinders and analyzed at Scott to determine if more detailed analyses were necessary.

Complete instrument calibrations were repeated every 30 days during continuous field work at a site.

NO_x converter efficiency was checked weekly. The calibration of the electrical total pressure meter was checked by comparison to the aneroid unit.

Before each engine emissions test, the analyzers were spanned and zeroed. After the test, the instrument zeroes and spans were checked. No attempt was made to readjust the analyzers unless excessive span or zero drift occurred. If instrument misadjustment was suspected the analyzers were zero and span checked then adjusted and then the new zero and span values logged.

1.3.3 Exhaust Emission Data

During an engine test the instrument readings, range data and analysis system parameters were logged on magnetic tape. Ten scans of

TABLE 1-8

MEL SPAN AND CALIBRATION GAS INVENTORY

Span and Working Gases in MEL

Gas Analysis	No. of Cylinders
Blended Air	1
Zero Grade N_2	1
Oxygen	1
60/40 Hydrogen/Helium	1
Propane 1540 ppm C_3	1
Propane 13.0 ppm C_3	1
CO 80.0 ppm	1
CO 225 ppm	1
CO 2500 ppm	1
CO 2500 ppm	1
CO_2 3.32%	1
CO_2 8.9%	1
NO 48.2 ppm	1
NO 94.0 ppm	1

Calibration Gases

Nominal Gas Concentration	No. of Cylinders
Propane 8 ppm	2
Propane 90 ppm	3
Propane 150 ppm	2
Propane 875 ppm	1
CO 60 ppm	1*
CO 80 ppm	3
CO 200 ppm	2
CO 580 ppm	1*
CO 900 ppm	1
CO 1800 ppm	1

TABLE 1-8
(Continued)

MEL SPAN AND CALIBRATION GAS INVENTORY

Calibration Gases

Nominal Gas Concentration	No. of Cylinders
CO 2500 ppm	1
CO 4200 ppm	1
CO 5900 ppm	1
CO_2 1.5%	1*
CO_2 4.5%	1
CO_2 6.0%	1*
CO_2 9%	2
CO_2 12%	1
NO 4.5 ppm	1
NO 9.4 ppm	1
NO 95 ppm	1
NO 240 ppm	1
O_2	2
Zero Grade N_2	3
Hydrocarbon-Free Air	2
H_2/He	2
Toluene 30 ppm	1
Propylene 42 ppm	1
Hexane 6 ppm	1

* Indicates CO plus CO_2 blend in N_2

the instruments were logged at each Category B sample point. Five scans of each instrument were logged at each Category A sample point. The scans were begun when the emissions readings were stabilized at each sampling point.

Smoke samples corresponding to a filter loading of 0.023 lbs. of sample air passing through each square inch of filter paper (W/A = 0.023) were taken at each sample point. The quantity of sample required was read from a prepared table of required sample volume versus sample temperature and sample pressure. The smoke data were entered on a test form, a sample of which is shown as Figure 1-11.

During the Category C testing, four smoke spot samples corresponding to W/A's of approximately .01, .015, .03 and .05 were taken. The true W/A at each point was determined from the recorded sample temperature and pressure and the wet test meter volume reading. These smoke spot samples were then used to plot the least-squares fit of smoke number (S/N) versus W/A. While the four smoke spots were being taken in the Category C tests, four repeat readings were taken on the emissions analyzers. Category C tests were always done using sample point number 3 of the Category B test sample point configuration. In actual practice, the Category C tests were done as an add-on to a Category B test.

1.3.4 Engine Operating Data

The engine operating data read off the test cell engine instrumentation were transcribed onto a test form supplied by Scott. A sample of this form is shown as Figure 1-12. The data entered on this form included engine thrust, low speed rotor RPM, high speed rotor RPM, fuel flow, air flow, test cell gauge pressure at engine inlet, bell mouth static pressure, bell mouth total pressure, engine pressure ratio, compressor inlet total temperature, exhaust gas temperature, turbine inlet temperature and exhaust nozzle area.

1.3.5 Engine History Data

Engine history data were also entered into the form of Figure 1-12. These data inlcuded the engine type and dash number, engine serial number and the engine total time.

Leave Blank
SET I.D.:________

SET 1492 3/1/75

U.S.A.F. EMISSIONS INVENTORY

SMOKE SAMPLE DATA

Page _____ of _____

Date:______________

Engine Model:____________ Scott Test No._____

Engine S/N:______________ Location:__________

Test Cell Test No.:______ Operator:__________

Sample Mode No.	Sample Point No.	Sample Temp. °F	Sample Press. PSIA	Sample Flow CFM	Sample Volume CF	W - A	Sample Reflect. R_s	Paper Reflect. R_w	S/N	Comments

FIGURE 1- 11

SET 1492 3/1/75

Leave Blank
SET I.D.: ______

U.S.A.F. EMISSIONS INVENTORY

ENGINE TEST DATA

Engine Model: ____________
Engine S/N: ____________
Test Cell Test No.: ________
Total Engine Time: ________ **Hrs.**
Air Flow-Method of Determination: ________
PERFORMANCE TEST: _____ **Pass** _____ **Fail**
If fail, Why? ____________________

SAMPLE LINE:
Temp. °F: ____________
Flow Rate: ____________
Sample Line Length ______ ft.

FUEL:
Type: ____________
Sp.Gravity: ____________
Sample No.: ____________

Date: ____________
Scott Test No.: ____________
Location: ____________
Test Cell Oper.: ____________
Scott Supervisor: ____________
Inst. Operator: ____________
Smoke Operator: ____________

	Time (Mil)	B P In HG	Dry Bulb Temp-°F	Wet Bulb Temp-°F	Dew Pnt. Temp-°F	Spec. Hum. #/#
TEST START						
TEST STOP						
[illegible]AGE						

Test No.	Mode	Nom. Pwr. Level	Thrust (Actual) (lbs.)	Fuel Flow (Act.) lbs/hr	Air Flow (Act.) lbs/sec	RPM (Actual) N_1	N_2	TURBINE PRESSURES P_{T_1} Cell Dep. In. H_2O Diff.	P_{S_2} Bell Mouth Static In.H_2O Diff.	P_{T_2} Bell Mouth Total In.H_2O Diff.	P_{T_3} Comp. Dish. PSIG	$P_{T_{5/7}}$ Turb. Disch. Total In. Mercury	EPR	TURBINE TEMP. °F T_{T_2} Comp. Inlet Total Temp.	$T_{T_{5/7}}$ EGT	TIT Turbine Inlet Temp.	Nozzle % Open		
1	IDLE	-																	
2	INT 1	75%																	
3	INT 2	85%																	
4	NOR	90%±																	
5	MIL	100%																	
6	MAX A/B	-																	

FIGURE 1-12

1.3.6 Ambient Air Data

The ambient air temperature, humidity and barometric pressure were recorded at the beginning and end of each engine test. The data were obtained from the test cell instruments and logged on the engine test data form.

1.4 DATA PROCESSING PROCEDURE

The system used to process the gas turbine emission data was a computerized system which accepted the magnetic tape recording generated by the MEL and processed it through to calculated mass emission rates. The procedure proceeded in two steps 1) conversion of raw data into engineering values and arrangement into computer files and 2) calculation of mass emission rates and generation of emission test reports.

1.4.1 Raw Data Reduction

The raw data reduction scheme is illustrated in Figure 1-13. Three parallel run streams produce the concentration data file, the engine/test data file and the smoke data file.

Gas Concentration Data Reduction

The magnetic tape recording produced by the MEL Data Acquisition system is a recording of the analysis instrument voltages and digitally encoded supporting data such as test number, run number, probe position, time of day, system status codes and instrument ranges. In the first step the magnetic tape recorded in EBCDIC* is read into the computer, converted to machine language, and arranged into a raw data file format. Figure 1-14 is a sample of raw data file format. This file is stored in the computer for future use and also output listed for the data analyst to examine. Any incorrect data can be corrected at this stage. Improper test or run codes logged at the time of the test can now be made correct. Data from an aborted run can be deleted. Also, inserted into this file on punch cards, are the span gas calibration data.

The corrected raw data were reduced to concentration units by

*Extended Binary Coded Decimal Interchange Code

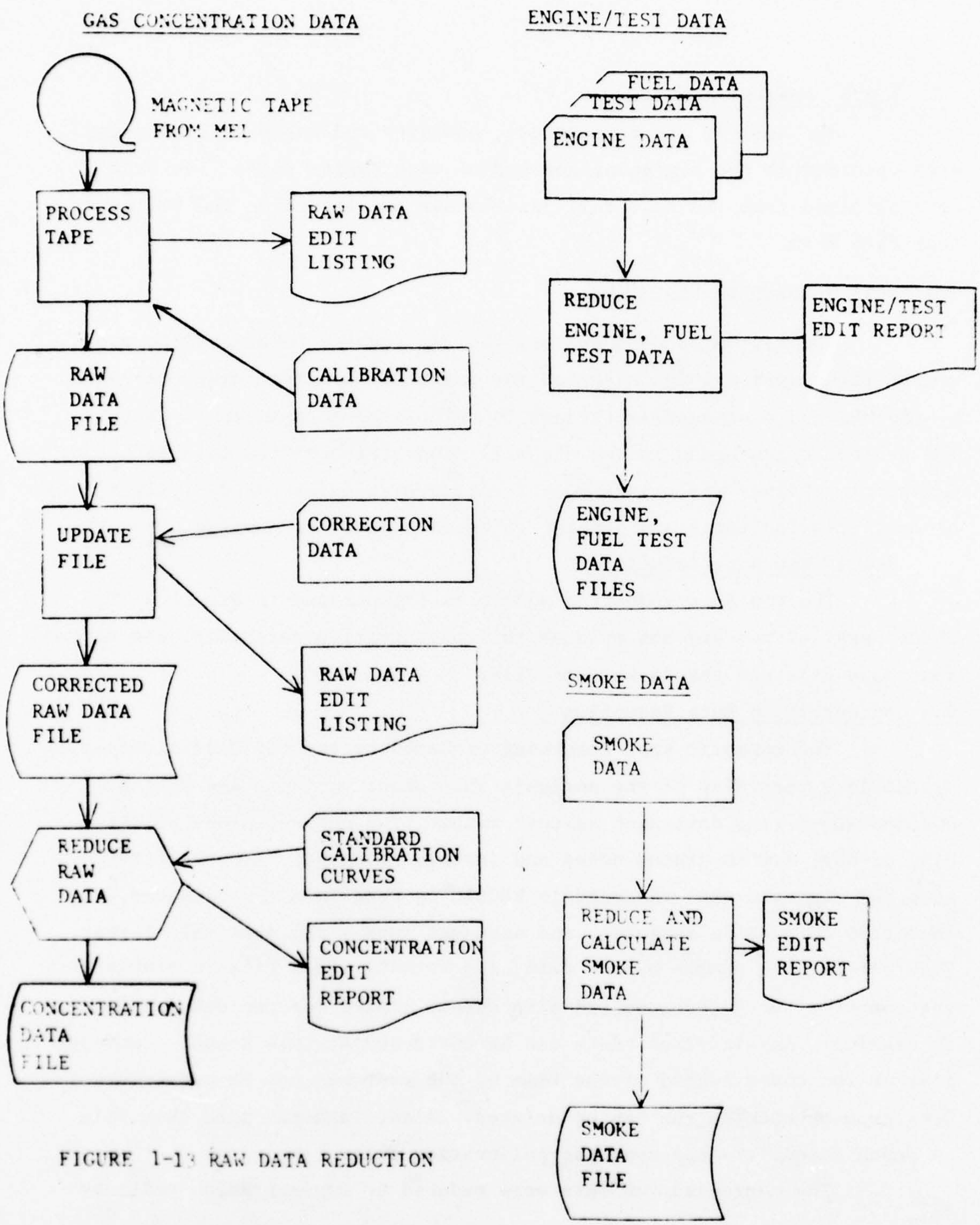


FIGURE 1-13 RAW DATA REDUCTION

INST RANGE

	CODE	RUN NO.	STATUS TIME	EDIT	STATUS	THC	NO_x	NO	LO CO	HI CO	CO_2	PROBE POS.	TOT PRESS	PROBE TEMP.	REF TEMP.
0DATA.L	RA0-2.														
DATA T7	RL70-5	12/03-20:10:39													
1.	A1129	2A 31 876	TPIR TF34		201025 GE LYNN		FUEL JP 5 GE TEST 7 DATA POINTS								
2.	A2129	2A 31 876	TPIR TF34		201025 GE LYNN		2045 HRS								
3.	C 129	2A 31 876	41.40	46.00	46.00	230.00	29.30	3.17	426.00	83.00	83.0025	00.00	230.00	8.90462	0.00 -.01 1.000
4.	C1129	1401	08801	AAAAAAAAADAA	09-122333	.1087	.0032	.0079	-.0063	.0030	.0038	-.1934	.0000	88.7	80.7
5.	C1129	1401	08802	AAAAAAAAADAA	09-122333	.0780	.0010	.0077	-.0066	.0036	.0020	-.1934	.0000	88.8	81.6
6.	C1129	1401	08803	AAAAAAAAADAA	09-122333	.0655	.0017	.0079	-.0062	.0054	.0011	-.1934	.0000	88.7	81.1
7.	C1129	1402	08801	AAAAAAAAADAA	09-233222	.0235	.0020	.0067	-.0001	.0014	.0071	-.1934	.0000	88.7	81.0
8.	C1129	1402	08802	AAAAAAAAADAA	09-233222	.0121	.0012	.0069	-.0010	.0025	.0068	-.1934	.0000	88.6	80.5
9.	C1129	1402	08803	AAAAAAAAADAA	09-233222	.0197	.0024	.0068	.0001	-.0036	.0086	-.1933	.0000	88.7	81.9
10.	C1129	1403	08801	AAAAAAAAADAA	09-344111	.0101	.0019	.0065	.0006	.0000	.0055	-.1933	.0000	88.7	81.7
11.	C1129	1403	08802	AAAAAAAAADAA	09-344111	.0086	.0020	.0066	.0005	-.0005	.0066	-.1934	.0000	88.7	80.3
12.	C1129	1403	08803	AAAAAAAAADAA	09-344111	.0093	.0018	.0066	.0008	-.0001	.0071	-.1934	.0000	88.6	78.8
13.	C1129	1404	08801	AAAAAAAAADAA	09-455333	.0017	.0019	.0065	-.0073	-.0033	.0047	-.1933	.0000	88.5	77.2
14.	C1129	1404	08802	AAAAAAAAADAA	09-455333	.0010	.0019	.0064	-.0061	-.0035	.0055	-.1934	.0000	88.5	78.2
15.	C1129	1404	08803	AAAAAAAAADAA	09-455333	.0020	.0018	.0064	-.0084	.0002	.0036	-.1933	.0000	88.4	77.6
16.	C1129	1405	08801	AAAAAAAAADAA	09-555333	-.0005	.0019	.0065	-.0079	.0051	.0053	-.1933	.0000	88.4	78.5
17.	C1129	1405	08802	AAAAAAAAADAA	09-555333	-.0005	.0019	.0065	-.0092	-.0009	.0038	-.1933	.0000	88.5	78.9
18.	C1129	1405	08803	AAAAAAAAADAA	09-555333	-.0005	.0019	.0065	-.0088	.0014	.0023	-.1934	.0000	88.5	79.0
19.	C1129	1501	08801	AAAAAAAAADAA	09-344222	-.0125	.0053	.0084	.0050	.0006	.0087	-.1932	.0000	88.8	79.3
20.	C1129	1501	08802	AAAAAAAAADAA	09-344222	-.0021	.0051	.0080	.0043	.0000	.0110	-.1932	.0000	88.8	78.5
21.	C1129	1501	08803	AAAAAAAAADAA	09-344222	-.0360	.0041	.0076	.0029	.0001	.0077	-.1932	.0000	88.7	77.1
22.	C1129	1407	09901	AAAAAAAAADAA	11-144333	.9476	.4550	.4528	.2969	.3259	.6886	-.1933	.0000	88.8	81.7
23.	C1129	1407	09902	AAAAAAAAADAA	11-144333	.9256	.4569	.4532	.2964	.3253	.6857	-.1934	.0000	88.8	82.2
24.	C1129	1407	09903	AAAAAAAAADAA	11-144333	.9296	.4554	.4510	.2986	.3261	.6870	-.1934	.0000	88.7	82.2
25.	C1129	1408	09901	AAAAAAAAADAA	11-244333	.1924	.4563	.4506	.2982	.3179	.6932	-.1933	.0000	88.8	79.9
26.	C1129	1408	09902	AAAAAAAAADAA	11-244333	.1840	.4574	.4496	.2972	.3213	.6913	-.1934	.0000	88.8	78.8
27.	C1129	1408	09903	AAAAAAAAADAA	11-244333	.2215	.4576	.4499	.2978	.3180	.6881	-.1933	.0000	88.7	78.8
28.	C1129	1410	09901	AAAAAAAAADAA	21-344222	.8196	.8556	.8214	.7542	.7522	.9154	-.1934	.0000	88.5	79.4
29.	C1129	1410	09902	AAAAAAAAADAA	21-344222	.8288	.8562	.8203	.7544	.7564	.9149	-.1934	.0000	88.6	79.3
30.	C1129	1410	09903	AAAAAAAAADAA	21-344222	.8198	.8547	.8187	.7539	.7612	.9131	-.1934	.0000	88.7	79.5
31.	C1129	1411	09901	AAAAAAAAADAA	21-455111	.1651	.3458	.3338	.5012	.3079	.6263	-.1934	.0000	88.8	81.7
32.	C1129	1411	09902	AAAAAAAAADAA	21-455111	.1645	.3466	.3337	.5016	.3086	.6248	-.1934	.0000	88.8	82.0
33.	C1129	1411	09903	AAAAAAAAADAA	21-455111	.1645	.3466	.3339	.5013	.3092	.6236	-.1933	.0000	88.7	81.9
34.	C1129	1502	09901	AAAAAAAAADAA	21-344222	.8850	.8599	.8177	.7521	.7481	.9118	-.1932	.0000	88.6	78.9
35.	C1129	1502	09902	AAAAAAAAADAA	21-344222	.8847	.8602	.8171	.7537	.7500	.9106	-.1932	.0000	88.6	79.8
36.	C1129	1502	09903	AAAAAAAAADAA	21-344222	.8822	.8613	.8165	.7528	.7536	.9136	-.1932	.0000	88.7	80.3
37.	C1129	1413	09901	AAAAAAAAADAA	41-544333	.9421	.0135	.0101	.0205	.0151	.0055	-.1934	.0000	88.6	80.3
38.	C1129	1413	09902	AAAAAAAAADAA	41-544333	.9383	.0117	.0115	.0235	-.0001	.0044	-.1933	.0000	88.6	80.2
39.	C1129	1413	09903	AAAAAAAAADAA	41-544333	.9378	.0069	.0129	.0235	-.0136	.0041	-.1934	.0000	88.7	79.3
40.	C2129	1546	08801	AAAAAAAAADAA	09-432212	.0068	.0102	.0085	.0071	.0008	.0087	.0760	.0000	107.7	83.3
41.	C2129	1546	08802	AAAAAAAAADAA	09-432212	.0058	.0094	.0069	.0063	-.0002	.0075	.0762	.0000	88.7	83.5
42.	C2129	1546	08803	AAAAAAAAADAA	09-432212	.0257	.0088	.0074	.0049	-.0005	.0057	.0762	.0000	85.1	82.4
43.	C2129	1547	09901	AAAAAAAAADAA	21-444212	.1760	.8452	.8031	.7552	.2952	.8931	-.0722	.0000	149.0	80.0

Figure 1-14. RAW Data

Note: Dimensions are in volts.

first adjusting the recorded voltages for instrument zero drift and then scaling the concentrations using the appropriate span factor. Since instrument calibrations were made at a minimum at the beginning and end of each test a time wise history of span drift and zero drift can be calculated for each data point time. Interpolated values of zero and span factor were used to adjust each instrument reading. The readings from the non-linear instruments (the NDIR's for CO and CO_2) were scaled using the standard calibration curve developed for each range of each instrument. A cubic polynomial routine was used for the non-linear curve fit. The total temperature thermocouple reading was also scaled from the recorded value using the cubic polynomial routine.

Total temperature was recorded three ways: 1) using an Iridium-Rhodium Iridium thermocouple recorded on a Copper-Constantan channel, 2) Using a Chromel-Alumel thermocouple recorded on a Copper-Constantan channel or 3) Using a Chromel-Alumel thermocouple recorded on a voltage channel. In reducing the thermocouple data the appropriate algorithm was used depending on the way in which the data were recorded.

The concentration edit report provided a step in which the analyst reviewed the data file for errors or omissions.

<u>Engine/Test Data Reduction</u>

The engine operating parameters are obtained from the test cell operators on a hand written log form. These data plus the "test" data which include the date, engine serial number, test number, and other labelling parameters are entered into the computer data processing system on punched cards. The computer then arranges the data into a file, converting the "as measured" engineering units to the units required for the test reports. The fuel analysis data are converted to H/C ratio. A listing is provided for editing.

<u>Smoke Data Reduction</u>

The smoke data are delivered from the field as a hand log of smoke densities and sample volumes, pressures and temperatures. The data are transfered to punch cards which are then input to the smoke data

reduction program. The output is a computer file and a listing of calculated smoke number and filter loading for each smoke sample. The listing is reviewed and edited of any errors.

1.4.2 Calculation of Mass Emission Rates

The second step in the data reduction process is the calculation of mass emission rates of the various pollutants. The technique is that of SAE ARP 1256* involving a carbon balance. Additionally the data are mass flow weighted. The measured concentrations at each sample point are weighted by the mass flow at that sample point. A mass flow weighted average concentration over the exhaust plane is then calculated. These mass flow weighted average concentrations are then used to calculate the emission rates by carbon balance.

The mass flow parameter is calculated from the exhaust total temperature and total pressure at each sample point. The mass flow parameter is the product of the exhaust gas density and velocity. Section 1.5.1 describes the mass weighting technique. The exhaust stream velocity is calculated from the total pressure and total temperature thusly:

First the Mach number is calculated

$$M = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P_o}{P_s}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \qquad (1)$$

p_o and p_s are the total pressure and static pressure in absolute units. γ is the ratio of specific heats and was selected from a table of γ versus temperature. The free stream temperature (T_s) is calculated from the total temperature (T_o)

$$T_s = \frac{T_o}{1 + \frac{\gamma-1}{2} M^2} \qquad (2)$$

The speed of sound (V_a) in the exhaust gas is

$$V_a = \sqrt{\gamma g R T_s} \qquad (3)$$

*Procedure for the Continuous Sampling and Measurement of Gaseous Emissions from Aircraft Turbine Engines, Society of Automotive Engineers, ARP 1256.

where g is the dimensioned constant 32.117 ft/sec^2 and R for air is $53.3 \frac{lb\text{-}ft}{^{o}R}$.

The exhaust velocity at each sample point is then:

$$V = (V_a)M \qquad (4)$$

and the exhaust gas density at each point is:

$$\rho = \frac{P_s}{\gamma R T_s} \qquad (5)$$

The mass flow at each point was obtained from the product of ρ and V and is in the units slugs per square foot per second.

Computer Routine

Figure 1-15 illustrates the step by step procedure used in converting the raw data to mass emission rates. The top row are the data inputs to the program. These data files are stored in the computer as a result of the first stage of data reduction where the records were converted to engineering units. These three records are the Engine/Test Data File, the Smoke Data File and the Concentration Data File. In the calculation process the mass weighting parameter ρV is calculated and used to mass weight the concentrations data. Then, the average mass weighted concentrations for each power setting is determined. The mass emission rates in pounds per thousand pounds of fuel are then calculated from the average mass weighted concentrations by carbon balance.

Calculations also performed at this time included a fuel/air ratio calculation based on the exhaust analysis and an air flow calculation if needed. For those test cell installations not having calibrated bell mouths the air flow was calculated from the bell mouth total and static pressures. The air-fuel ratio calculated from the emissions analysis is used for comparison to the measured air-fuel ratio as a check on the quality of the emissions analysis.

The mass emission rate in pounds per hour of each pollutant is

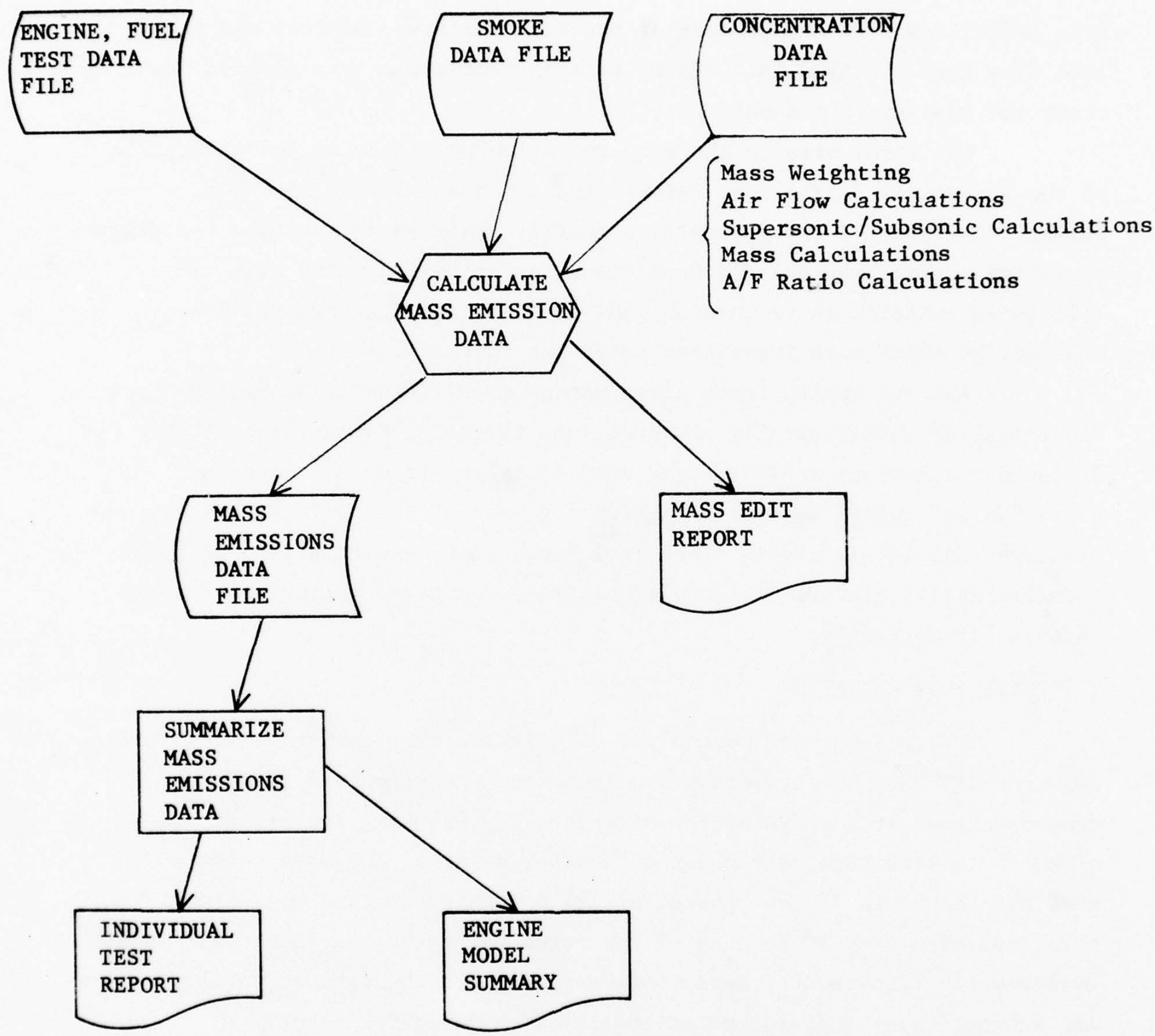


FIGURE 1- 15 MASS EMISSION RATE CALCULATION SYSTEM

also calculated from the product of the rate per pound of fuel and the fuel flow rate. A Mass Edit report is then produced so the analyst can check the quality of the data.

The final step in the data reduction procedure is the production of the Individual Engine Test Reports and the Model Summaries Report. Selected portions of the raw data, primarily those which describe the engine operating parameters and test conditions, are combined along with the calculated emission rates into an Individual Engine Test Report, the contents of which were prescribed under the Contract.

All the engine tests of an engine model (usually numbering about ten tests) are statistically combined into the Model Summary report. Standard statistical routines were used to calculate mean, standard deviation and coefficient of variation for each of the pollutants measured. Similar treatment is given to the fuel flow, smoke and thrust to produce a comprehensive picture of the variability encountered during the testing of each engine family.

1.5 MASS FLOW WEIGHTING

The recommended method for calculating mass emission rates from a source with non-uniform cross-sectional concentrations is to measure the concentrations at a large number of points representing centers of equal area and to simultaneously measure flow parameters. The mass emission rate for each area is the product of its concentration and mass flow. The total emission rate is the sum of the rates for each area. The additional measurements required for mass flow weighting are the exhaust total pressure and exhaust total temperature at the emissions sampling point.

1.5.1 Mass Flow Calculations

Mass flow rates were first calculated from the pressure and temperature data. The mass flow parameter (ρV) at each grid point was calculated from the static, barometric and total pressure and the total temperature using equations (1) through (5) above.

The mass flow per unit area (ρV) at each point was obtained from the product of ρ and V and is in the units slugs/ft^2-sec.

1.5.2 Emissions Weighting

The measured concentration at each point was weighted by the mass flow at each point and the average mass weighted concentration for each measured exhaust gas constituent was determined using the relationship:

$$\text{Mass weighted average concentration} = \frac{\sum_{1}^{n} C_n \rho_n V_n}{\sum_{1}^{n} \rho_n V_n}$$

where C_n is the concentration of the pollutant specie at each point, and $\rho_n V_n$ is the mass flow at each point.

Where mass flow data were missing due to either a missing or erroneous total temperature or total pressure reading the emissions data were area weighted. In the area weighted case the concentrations of each pollutant measured at each point were summed and divided by the number of sample points. The Individual Engine Test Reports are annotated to indicate whether mass weighting or area weighting were employed.

1.6 PRESENTATION OF MEASURED DATA

This section describes the various formats used to report the raw data gathered during the program. These reports record all the measured data including emissions concentrations, engine operating parameters and supplemental information on test conditions, instrument operating conditions and ambient air conditions. There are four reports which contain these raw data. They are 1) Concentration Edit Report, 2) Engine Test Data Edit, 3) Mass Data Calculations and 4) Smoke Edit Report. The word "Edit" has been used in naming these reports since in the process of entering the raw data into the computer, these reports were used to examine and 'edit' the data in order to ensure completeness and accuracy. At the edit stage, obvious outliers or errors in labelling were either deleted or corrected. This approach was used to prevent

wasteful processing of erroneous data. Each of these edit reports are described below.

1.6.1 Concentration Edit Report

A sample of a Concentration Edit Report is presented as Figure 1-16. This report contains the individual readings in voltage of the emission analyzers for THC, NO_x, NO, CO (High), CO (Low) and CO_2 along with the total temperature thermocouple channels. The average of thirty total pressure readings is entered at the left along with the sample probe axis and position and mode/sample number. Above each data column appear both the instrument span factor and zero adjustment interpolated by time difference between the beginning and end instrument calibrations. The average voltage reading and reduced concentration appear below each column of readings. The readings in each column have been adjusted for span factor and zero adjustment.

1.6.2 Engine Test Data Edit Report

A sample of an Engine Test Data Report is shown in Figure 1-17. This report logs all the engine operating data. These readings are averages of two readings taken by the test cell operators at the beginning and end of the emissions test at each power setting. The figure is anotated with explanations of the labels and engineering units used.

1.6.3 Smoke Edits

A sample smoke edit is presented as Figure 1-18. W/A is the weight of gas sample divided by the filter area calculated from the listed values of sample temperature, pressure and volume. In all category A and B tests the target value for W/A was .023 pounds per square inch.

1.6.4 Mass Calculations Edit Report

This report, illustrated in Figure 1-19, is a sample point by sample point listing of the measured concentration and exhaust physical parameters. The exhaust parameters are used to calculate the mass flow weighting parameter, ρV at each sample point. The weighting parameter has the units of mass flow per unit area (slugs per square foot per second).

Probe Position (Axis and Extension Distance)

Scott Test Number and Test Category

Test Date

Engine Type and Serial Number

Test Location

SCOTT ENVIRONMENTAL TECHNOLOGY INC. SET 1492-013-0177 REPORT DATE 02/08/77
USAF TURBINE ENGINE EMISSIONS INVENTORY USAF CONTRACT F29601-75-C-0046
CONCENTRATION EDIT REPORT SCOTT TEST 135,TYPE 8 9/16/76 TF34100 # 205085 GE LYNN FIELD TEST 7

Ratio of Span to Standard Span

Test Mode and Sample Point No.

Zero Adjustment in Volts

Thermocouple Run Readings

Total Pressure

Thermocouple Reduced Value

	THC RNG	THC VOLTS	NOX RNG	NOX VOLTS	NO RNG	NO VOLTS	CO-HI RNG	CO-HI VOLTS	CO-LO RNG	CO-LO VOLTS	CO2 RNG	CO2 VOLTS	TEMP.- F. INPUT	TEMP.- F. REFER
MODE-POINT : 1-01														
SPAN/ZERO ADJ.	1.07	.0004	.99	.0002	1.04	.0009	1.00	.0025	1.00	-.0005	1.02	-.0019		
SAMPLE DATA :														
TIME : 2040	50.00	.2527	25.00	.5617	10.00	.0767	2	.3842	1	1.0362	3	.4847	130.3	80.5
PROBE POS.: +30		.2542		.5577		.0782		.3837		1.0375		.4849	130.3	80.1
-7.65 IN.		.2544		.5600		.0778		.3851		1.0388		.4835	130.4	81.1
PRESS.: 15.02 PSIA		.2560		.5614		.0784		.3837		1.0360		.4840	130.1	81.6
		.2602		.5599		.0785		.3835		1.0422		.4845	130.4	81.6
		.2561		.5582		.0775		.3835		1.0410		.4855	130.2	81.6
AVERAGE :		.2556		.5598		.0778		.3839		1.0389		.4845	130.3	81.1
CONCENTRATION :	639.05 PPMC		14.30 PPMV		.78 PPMV		1179.56 PPMV		.00 PPMV		2.16 % VOL		401.0 DEG.F	
MODE-POINT : 1-02														
SPAN/ZERO ADJ.	1.07	.0004	.99	.0002	1.04	.0008	1.00	.0025	1.00	-.0005	1.02	-.0020		
SAMPLE DATA :														
TIME : 2044	50.00	.2263	25.00	.5955	10.00	.0606	2	.3524	1	.9774	3	.4823	153.1	77.7
PROBE POS.: +30		.2240		.5950		.0613		.3524		.9821		.4898	153.5	78.9
-6.53 IN.		.2271		.5936		.0602		.3531		.9875		.4841	153.7	78.2
PRESS.: 15.04 PSIA		.2240		.5938		.0613		.3535		.9675		.4887	153.8	78.7
		.2275		.5940		.0609		.3527		.9879		.4825	153.9	78.6
		.2230		.5963		.0599		.3536		.9896		.4890	153.9	79.8
AVERAGE :		.2253		.5947		.0607		.3529		.9853		.4861	153.6	78.6
CONCENTRATION :	563.28 PPMC		14.87 PPMV		.61 PPMV		1082.64 PPMV		1073.42 PPMV		2.17 % VOL		604.3 DEG.F	

** NOTE ** DATA MARKED WITH AN ASTERISK (*) NOT INCLUDED IN AVERAGE

Readings of each instrument in volts corrected for span factor and zero adjustment

Figure 1-16 Concentration Edit Sample Report

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SCOTT ENVIRONMENTAL TECHNOLOGY INC. SET 1992-013-0177 REPORT DATE 02/03/77
USAF TURBINE ENGINE EMISSIONS INVENTORY USAF CONTRACT F29601-75-C-0046
EDIT REPORT - ENGINE TEST DATA

SCOTT TEST NUMBER 136, TYPE B TEST DATE : 9/22/76 ENGINE 20, NUMBER 6

ENGINE TYPE & MODEL : TF34-100
ENGINE SERIAL # : 205089
TOTAL ENGINE TIME : 0 HRS.
PERFORMANCE TEST RESULTS : PASS

AIR FLOW MEASUREMENT METHOD : MEASURED

TEST LOCATION : GE LYNN, MA
TEST CELL NUMBER : 12
TEST CELL OPERATOR : D
SCOTT SUPERVISOR : ZGT
INSTRUMENT OPERATOR : PR
SMOKE OPERATOR : PR

TEST ENVIRONMENTAL CONDITIONS :

	START	FINISH
TEST TIME (MIL.TIME) :	710	1000
INLET AIR TEMP.(DEG.F) :	50.4	58.3
ATMOSPHERIC PRESS.(IN.HG) :	29.66	29.66
RELATIVE HUMIDITY (%) :		
INLET AIR HUMIDITY - (GM H2O/GM DRY AIR) :	0.0069	0.0069

SAMPLE LINE :
FLOW RATE : 23 LPM
TEMPERATURE : 300 DEG.F
LENGTH : 100 FT.

FUEL ANALYSIS :
SAMPLE # : 30
TYPE : JP-4
WT.% CARBON : 86.04
WT.% HYDROGEN : 14.28
WT.% SULFUR : C.02
H/C RATIO-ATM.: 1.99
C/H RATIO-MASS: 6.03

TEST MODE	% RATED POWER	THRUST #	FUEL FLOW #/HR	N1 SPEED RPM	N2 SPEED RPM	PT1 CDTP IN.H2O	PT2 CITP IN.H2O	PS2 CISP IN.H2O	PT3 CDTP PSIG	PT5/PT7 TDTP IN.HG	TT2 CIT DEG.F	TT5/TT7 EGT DEG.F	NOZZLE OPEN. %
IDLE	7	643	395	2004	11336	0.10	0.02		33.5		51		
INTERMED. 1	12	1031	490	2529	12411	0.06	0.14		49.3		51		
APPROACH	34	2586	902	3927	13800	0.64	0.91		100.5		52		
CRUISE	59	4407	1288	5020	14958	1.16	1.77		150.8		54		
MAX.CONT.PWR	100	7416	2545	6203	16334	2.21	3.90		224.8		56		
TAKE-OFF	125	8001	2794	6916	17052	2.08	4.18		238.3		57		

Low Speed Rotor

High Speed Rotor

Cell Depression Total Pressure (gage)

Compressor Inlet Total Pressure (gage)

Static Pressure at Bellmouth Throat (gage)

Compressor Discharge Total Pressure (psig)

Turbine Discharge Total Pressure (in Hg gage)

Compressor Inlet Total Temperature

Turbine Discharge Total Temperature (Exhaust Gas Temp.)

Nozzle Position
Minimum = 0%
Maximum = 100%

Figure 1-17 Engine Edit Data Sample Report

SCOTT ENVIRONMENTAL TECHNOLOGY INC. | SET 1492-015-0177 | REPORT DATE 02/17/77
USAF TURBINE ENGINE EMISSIONS INVENTORY | | USAF CONTRACT F29601-75-C-0046
EDIT REPORT - SAMPLE POINT SMOKE DATA

Smoke Sample Temperature and Pressure

W/A Calculated from Sample Volume, Pressure and Temperature

** RUN 137 **

SAMPLE POINT	TEMP DEG.F	PRESS PSIA	FLOW CFM	VOLUME CF	W/A #/SQ.IN	SAMPLE REFL.	PAPER REFL.	SN
111	80.0	14.8	.50	.455	.0232	98.50	100.00	1.50
101	80.0	14.8	.50	.455	.0232	99.00	100.00	1.00
112	85.0	14.8	.50	.459	.0232	98.00	100.00	2.00
102	85.0	14.8	.50	.459	.0232	97.50	100.00	2.50
113	85.0	14.8	.50	.459	.0232	97.00	100.00	3.00
103	85.0	14.8	.50	.459	.0232	95.00	100.00	5.00
114	85.0	14.8	.50	.459	.0232	95.00	100.00	5.00
104	85.0	14.8	.50	.459	.0232	95.50	100.00	4.50
115	85.0	14.8	.50	.459	.0232	96.00	100.00	4.00
105	85.0	14.8	.50	.459	.0232	95.50	100.00	4.50
116	85.0	14.8	.50	.459	.0232	96.50	100.00	3.50
106	85.0	14.8	.50	.459	.0232	96.00	100.00	4.00
211	85.0	14.8	.50	.459	.0232	97.00	100.00	3.00
212	85.0	14.8	.50	.459	.0232	99.00	100.00	1.00
202	85.0	14.8	.50	.459	.0232	98.00	100.00	2.00
213	85.0	14.8	.50	.459	.0232	98.50	100.00	1.50
203	85.0	14.8	.50	.459	.0232	98.00	100.00	2.00
214	85.0	14.8	.50	.459	.0232	99.00	100.00	1.00
204	85.0	14.8	.50	.459	.0232	99.00	100.00	1.00
215	85.0	14.8	.50	.459	.0232	100.00	100.00	.00
205	85.0	14.8	.50	.459	.0232	100.00	100.00	.00
216	85.0	14.8	.50	.459	.0232	99.00	100.00	1.00
206	85.0	14.8	.50	.459	.0232	92.50	100.00	7.50
311	85.0	14.8	.50	.459	.0232	95.50	100.00	4.50
301	85.0	14.9	.50	.459	.0232	98.00	100.00	2.00
312	85.0	14.8	.50	.459	.0232	97.00	100.00	3.00
302	85.0	14.8	.50	.459	.0232	97.00	100.00	3.00
313	85.0	14.8	.50	.459	.0232	97.00	100.00	3.00
303	85.0	14.8	.50	.459	.0232	96.50	100.00	3.50
314	85.0	14.8	.50	.459	.0232	96.00	100.00	4.00
304	85.0	14.9	.50	.459	.0232	97.00	100.00	3.00
315	85.0	14.8	.50	.459	.0232	96.00	100.00	4.00
305	85.0	14.8	.50	.459	.0232	96.00	100.00	4.00
316	85.0	14.8	.50	.459	.0232	94.50	100.00	5.50
306	85.0	14.8	.50	.459	.0232	96.50	100.00	3.50
411	85.0	14.8	.50	.459	.0232	97.00	100.00	3.00
401	85.0	14.8	.50	.459	.0232	98.00	100.00	2.00
412	85.0	14.8	.50	.459	.0232	97.00	100.00	3.00
402	85.0	14.8	.50	.459	.0232	99.00	100.00	1.00
413	85.0	14.8	.50	.459	.0232	96.50	100.00	1.50

.00 means S/N = 0

Engine power mode and sample point number.
101 indicates power mode #1 idle and sample point 01.

Figure 1-18 Smoke Edit Sample Report

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SCOTT ENVIRONMENTAL TECHNOLOGY INC. SET 1492-013-0177 REPORT DATE 02/08/77
USAF TURBINE ENGINE EMISSIONS INVENTORY USAF CONTRACT F29601-75-C-0046
EDIT REPORT - MASS DATA CALCULATIONS

Scott Test No.

Engine Mode and Thrust

Note: Units are Slugs/cu.ft

************ C O N T . R U N 135 ************

Test Category

ENGINE TYPE : TF34-100 ENGINE SN : 205085 TEST TYPE : B
BP : 30.21 IN.HG IAT : 62.6 DEG.F FUEL : # 29 - JP-5 H/C RATIO(ATM) : 1.90 FUEL SULFUR : .03 %

Engine and Fuel Data

***** MODE 7 - MAX.REDLINE (THRUST = 9206 #) *****

Actual Fuel/Air Ratio from fuel flow and air flow

PT1 = 3.49 IN.H2O PT2 = 6.06 IN.H2O PS2 = .00 IN.H2O PT3 = 276.1 PSIG PT5/7 = .0 IN.HG
EPR = 1.015 FUEL FLOW = 3315. #/HR AIR FLOW = 165600. #/HR ACTUAL F/A RATIO = .020

* SAMPLE POINT * NO	LOCATION	TEMP. DEG.F	PTOT PSIA	DENS. (RHO)	EXH.VEL FT/SEC	MASS FL. (RHO*V)	THC PPMC	CO PPM	CO2 %	NOX PPM	NO PPM	NO2 PPM	*--- SMOKE ---* SN	#/A
1	+30, -7.7	910.0	20.0	.0010	1176.22	1.1537	.48	42.44	4.19	144.13	120.73	23.40	21.00	.0231
2	+30, -6.6	914.0	19.8	.0010	1159.28	1.1306	.48	52.88	4.41	148.74	123.90	24.84	21.00	.0231
3	+30, -5.1	891.0	19.3	.0010	1100.78	1.0844	.51	39.95	3.98	133.17	110.93	22.24	17.00	.0231
4	+30, -2.9	877.0	19.5	.0010	1114.66	1.1130	1.05	38.14	3.90	130.49	109.15	21.34	20.50	.0231
* 5	+30, -.1	882.0	18.7	.0010	1033.49	1.0162	3.29	32.74	3.73	123.82	103.56	20.26	18.00	.0231
AVERAGE : NUM.		898.0	19.6	.0010	1137.78	1.1204	.63	43.35	4.12	139.13	116.18	22.96	19.87	.0231
MASS-WGHTD.							.63	43.40	4.12	139.25	116.28	22.97		

Mass Weighted Concentrations and Averages

CALCULATED F/A RATIOS FOR ABOVE AVERAGE CONCENTRATIONS : AREA-WGHTD.(NUM) = .020 , MASS-WGHTD. = .020

MASS EMISSIONS :

	---- THC --- #/1000#	#/HR	*---- CO ----* #/1000#	#/HR	*---- CO2 ---* #/1000#	#/HR	*---- NOX ---* #/1000#	#/HR	*---- NO ----* #/1000#	#/HR	*---- NO2 ---* #/1000#	#/HR	* SOX * #/HR
AREA-WGHTD.	.02	.06	2.11	7.0	3157.	10466.	11.15	36.95	9.31	30.85	1.84	6.10	1.99
MASS-WGHTD.	.02	.06	2.12	7.0	3157.	10466.	11.15	36.96	9.31	30.86	1.84	6.10	1.99

* MID-POINT - NOT INCLUDED IN AVERAGES

Mass Emission Rates

************* E N D R U N 135 *************

Calculated Fuel/Air Ratio based on measured emission concentrations. For comparison to the actual fuel/air ratio.

Figure 1-19 Mass Calculation Edit Sample Report

In calculating the mass weighted average concentration, the measured concentration at each sample point is multiplied by the ρV value at each sample point. The sum of the mass weighted concentrations are then divided by the sum of the mass flow parameters to obtain the average mass weighted concentration of each parameter. Algebraically expressed, the mass weighted average concentration of CO for instance is $C = \frac{\Sigma[(CO)(\rho V)]}{\Sigma(\rho V)}$. Both area weighted and mass weighted concentration averages are listed. When one of the exhaust parameters such as total temperature or pressure was missing average mass weighted concentration could not be calculated. In such case or when a rake probe was used, the data are presented as area-weighted averages only.

Both mass weighted and area weighted emission indeces are listed at the bottom of the page allowing comparison between the two. Preference is given to the mass weighted emission index when transferring these data to the Individual Engine Report file.

1.6.5 Test Log

The test log is a tabular listing of all the engine tests performed during this program. It provides a cross-reference of test numbers and test codes. Figure 1-20 is a sample of a test log. Engines used for more than one test can be quickly spotted using this log. For instance, Scott test Numbers 18 and 19 (a Category B and a Category C test) were both done on Engine 1, replicate 11 (J69-T25 S/N 321612). Also easily correlated with this table are the fuel sample number, test location, test category, engine serial number, engine type and test date.

SCOTT ENVIRONMENTAL TECHNOLOGY INC. REPORT DATE 07/19/77
USAF TURBINE ENGINE EMISSIONS INVENTORY USAF CONTRACT F29601-75-C-0046

TEST LOG

Indicates Engine 1, Test 03

Engine Number

Replicate Number

Test Category

Location (Neosho)

Fuel Sample Number

SCOTT TEST #	TEST CAT.	FIELD TEST #	DATE	ENGINE TESTED	ENGINE S/N	TEST LOCATION	TEST ID ENG#	REPL#	TC	LOC#	FS#	COMMENTS
1	B	101	03/11/75	J69-T25	321901	TELEDYNE,NEO	1	1	B	1	1	
2	B	102	03/12/75	J85-5	231118	TELEDYNE,NEO	2	1	B	1	1	PART.A/B
3	B	103	03/14/75	J69-T25	321142	TELEDYNE,NEO	1	2	B	1	1	
4	B	104	03/17/75	J69-T25	321989	TELEDYNE,NEO	1	3	B	1	1	
5	B	105	03/18/75	J69-T25	401301	TELEDYNE,NEO	1	4	B	1	1	
6	A	106	03/18/75	J69-T25	401565	TELEDYNE,NEO	1	5	A	1	1	
7	B	107	03/19/75	J69-T25	321512	TELEDYNE,NEO	1	6	B	1	1	
8	B	108	04/01/75	J69-T25	401664	TELEDYNE,NEO	1	7	B	1	2	
9	B	109	04/01/75	J69-T25	321492	TELEDYNE,NEO	1	8	B	1	2	
10	B	110	04/02/75	J69-T25	400365	TELEDYNE,NEO	1	9	B	1	3	
11	B	111	04/02/75	J69-T25	321322	TELEDYNE,NEO	1	10	B	1	3	
12	B	112	04/03/75	J85-5	230232	TELEDYNE,NEO	2	2	B	1	3	NO A/B
13	B	113	04/03/75	J85-5	230859	TELEDYNE,NEO	2	3	B	1	3	NO A/B
14	B	114	04/04/75	J85-5	232700	TELEDYNE,NEO	2	4	B	1	3	NO A/B
15	B	115	04/07/75	J85-5	231687	TELEDYNE,NEO	2	5	B	1	3	NO A/B
16	B	116	04/08/75	J85-5	232436	TELEDYNE,NEO	2	6	B	1	3	NO A/B
17	B	117	04/09/75	J85-5	231244	TELEDYNE,NEO	2	7	B	1	3	NO A/B
18	B	118	04/10/75	J69-T25	321612	TELEDYNE,NEO	1	11	B	1	3	
19	C	118	04/10/75	J69-T25	321612	TELEDYNE,NEO	1	11	C	1	3	
20	A	119	04/11/75	J85-5	232078	TELEDYNE,NEO	2	8	A	1	3	SMK-SAME
21	B	120	04/14/75	J85-5	232810	TELEDYNE,NEO	2	9	B	1	3	
22	C	120	04/14/75	J85-5	232810	TELEDYNE,NEO	2	9	C	1	3	
23	B	121	04/14/75	J85-5	232437	TELEDYNE,NEO	2	10	B	1	3	
24	C	121	04/14/75	J85-5	232437	TELEDYNE,NEO	2	10	C	1	3	
25	B	201	05/02/75	J60-P5	637067	ANDREWS	3	1	B	2	4	
26	B	202	05/05/75	J60-P3	637236	ANDREWS	3	2	B	2	4	
27	B	203	05/06/75	J60-P3	637285	ANDREWS	3	3	B	2	4	
28	B	204	05/08/75	J60-P3	636815	ANDREWS	3	4	B	2	4	
29	B	205	05/12/75	J60-P56	636976	ANDREWS	3	5	B	2	4	
30	A	206	05/13/75	J60-P58	636920	ANDREWS	3	6	A	2	4	
31	B	207	05/15/75	J60-P58	637064	ANDREWS	3	7	B	2	4	
32	C	207	05/15/75	J60-P58	637064	ANDREWS	3	7	C	2	4	
33	A	208	05/27/75	J60-P3	637234	ANDREWS	3	8	A	2	4	
34	B	209	05/27/75	J60-P3	636786	ANDREWS	3	9	B	2	4	
35	C	209	05/27/75	J60-P3	636786	ANDREWS	3	9	C	2	4	
36	A	210	05/28/75	J60-P58	636975	ANDREWS	3	10	A	2	4	NO GOOD
37	B	211	05/28/75	J60-P3	636645	ANDREWS	3	11	B	2	4	
38	B	301	06/16/75	J79-15	420655	KELLY AFB,TX	4	1	B	3	5	
39	B	302	06/19/75	J79-15	434487	KELLY AFB,TX	4	2	B	3	5	

Same Engine; Two Test Categories Performed

Figure 1-20 Engine Test Log Sample

2.0 INDIVIDUAL ENGINE TEST REPORTS

These reports list the results of each individual engine test. They are organized by engine operating mode. Figure 2-1 is an example of an Individual Engine Test Report. Volume II contains the Individual Engine Test Reports.

2.1 DATA PRESENTATION

The test results are grouped into eleven sections on the report page. Section 1 at the upper left contains the "Scott test number". This is a unique number used to catalog each engine test. Test Category (A, B or C) is contained in this section. At the top center of the page (section 2) is the test date. Section 3 contains the "Scott Engine I.D.". This label denotes the engine type and replicate number. For instance, in the example shown, Engine 1 means that this is a report on the J69 engine; number 11 means that this is a report on the eleventh J69 engine tested. Section 4 contains the specified engine data; serial number, total time, engine type and model and a remark as to whether the engine passed or failed the performance test. Section 5 is the air flow measurement type. "Bell mouth" means the air flow was calculated from either measured total pressure and static pressure at the throat, or from a static pressure measurement only assuming a long radius nozzle. "Measured" means that the air flow data was supplied by the test cell from pressure readings and a calibrated bell mouth. Section 6 lists the ambient air parameters at the beginning and end of the test. Section 7 lists the sample line conditions. Section 9 is the report of the analysis of the fuel sample taken at the time of the test. The hydrogen, carbon and sulfur content are reported along with the H/C mol ratio and C/H mass ratio.

Section 10 is the main body of the report and contains the main engine operating parameters and exhaust emissions analyses at each power mode studied. Section 10 contains the calculated emission rates in both pounds per thousand pounds of fuel and pounds per hour. At the bottom of Section 11, a note indicates whether the emission rates are mass-weighted

SCOTT ENVIRONMENTAL TECHNOLOGY INC. SET 1492-D14-0177 REPORT DATE 02/04/77
USAF TURBINE ENGINE EMISSIONS INVENTORY USAF CONTRACT F29601-75-C-0046
INDIVIDUAL ENGINE TEST REPORT

(1) Test Number
(2) Test Category
(3) Scott Engine ID

SCOTT TEST NUMBER 135, TYPE B TEST DATE : 9/16/76 ENGINE 20, NUMBER 5

ENGINE TYPE & MODEL : TF34-100
ENGINE SERIAL # : 205085
TOTAL ENGINE TIME : 0 HRS.
PERFORMANCE TEST RESULTS : PASS

(4) Engine Data

TEST LOCATION : GE LYNN, MA
TEST CELL NUMBER : 12
TEST CELL OPERATOR : N
SCOTT SUPERVISOR : Z6T
INSTRUMENT OPERATOR : PR
SMOKE OPERATOR : DJO

(7) Sample Line Data

(8) Test Operators

AIR FLOW MEASUREMENT METHOD : MEASURED

(5) Air Flow Measurement

(6)

TEST ENVIRONMENTAL CONDITIONS :

	START	FINISH
TEST TIME (MIL.TIME) :	2035	2250
INLET AIR TEMP.(DEG.F) :	64.8	60.4
ATMOSPHERIC PRESS.(IN.HG) :	30.21	30.21
RELATIVE HUMIDITY (%) :		
INLET AIR HUMIDITY - (GM H2O/GM DRY AIR) :	0.0110	0.0110

SAMPLE LINE :
FLOW RATE : 23 LPM
TEMPERATURE : 300 DEG.F
LENGTH : 100 FT.

FUEL ANALYSIS :
SAMPLE # : 29
TYPE : JP-5
WT.% CARBON : 86.59
WT.% HYDROGEN : 13.69
WT.% SULFUR : 0.03
H/C RATIO-ATM.: 1.90
C/H RATIO-MASS: 6.33

(9) Fuel Report

(10) These concentrations are mass weighted

TEST MODE	% RATED POWER	THRUST #	FUEL FLOW #/HR	AIR FLOW #/HR	F/A ACT	F/A CALC	EPR	THC PPMC	CO PPM	CO2 %	NOX PPM	NO PPM	NO2 PPM	SMOKE SN	SMOKE W/A
IDLE	7	540	390	31680	.012	.011	1.000	638.26	1162.53	2.13	14.07	0.64	13.44	2.75	0.0232
INTERMED. 1	12	812	457	40320	.011	.010	1.001	376.27	759.75	1.96	16.36	0.75	15.61	2.38	0.0232
APPROACH	34	2608	925	60640	.011	.011	1.003	19.54	169.51	2.22	37.02	25.16	11.85	1.25	0.0232
CRUISE	59	4486	1519	109800	.014	.014	1.006	2.47	50.34	2.78	60.28	48.64	11.64	0.50	0.0232
MAX.CONT.PWR	100	7657	2649	148320	.018	.018	1.011	1.50	37.68	3.64	107.80	89.34	18.46	5.25	0.0232
TAKE-OFF	125	8241	2888	154800	.019	.019	1.013	0.82	37.55	3.82	117.38	97.28	20.10	8.25	0.0231
MAX.REDLINE	130	9206	3315	165600	.020	.020	1.015	0.63	43.40	4.12	139.25	116.28	22.97	19.88	0.0231

EXHAUST MASS EMISSION INDICES :

(11) Mass Weighted emissions

	# / 1000# FUEL THC	CO	CO2	NOX	NO	NO2	# / HR THC	CO	CO2	NOX	NO	NO2	SOX
IDLE	31.76	101.02	2915	2.01	0.09	1.92	12.39	39.4	1137	0.78	0.04	0.75	0.23
INTERMED. 1	20.85	73.52	2988	2.60	0.12	2.48	9.53	33.6	1365	1.19	0.05	1.13	0.27
APPROACH	1.00	15.22	3134	5.46	3.71	1.75	0.93	14.1	2899	5.05	3.43	1.62	0.55
CRUISE	0.10	3.64	3154	7.16	5.78	1.38	0.16	5.5	4792	10.88	8.78	2.10	0.91
MAX.CONT.PWR	0.05	2.08	3157	9.77	8.10	1.67	0.13	5.5	8363	25.88	21.45	4.43	1.59
TAKE-OFF	0.02	1.97	3157	10.14	8.40	1.74	0.07	5.7	9118	29.27	24.26	5.01	1.73
MAX.REDLINE	0.02	2.12	3157	11.15	9.31	1.84	0.06	7.0	10466	36.96	30.86	6.10	1.99

** AVERAGE CONCENTRATION AND MASS EMISSION DATA ARE MASS-WEIGHTED.

Indicates mass weighting was possible (all data available)
If mass weighting was not possible due to missing data, the sample point concentrations were area weighted and so designated on this line.

Figure 2-1 Individual Engine Test Sample Report

or area weighted. When either the exhaust velocity or density were missing the emissions were area weighted. Measurements based on the use of a rake probe were considered to be area-weighted.

3.0 MODEL SUMMARY REPORTS

Model Summary reports are a statistical review of the emissions data gathered on each engine type. The maximum and minimum values of measured emission index (pounds per thousand pounds of fuel) and emission rate (pounds per hour) are listed for each of the exhaust species. Calculated values of the mean, standard deviation and coefficient of variation are presented. The data are arranged in order of power setting. Figure 3-1 is a sample of a Model Summary Report. Volume III contains the Model Summary Reports. The engine model is entered at the upper left. In the center are the test locations and a note on which set of data are presented. Two sets of Model Summaries were developed one for all engine tests and one for the Category B tests only. The model summary for the Category B tests only is the more statistically significant since these were the tests done on the largest number of engines of a given type. The number of observations of each parameter/power setting is included for use in gauging the statistical significance.

The widest variations in emission index are those of the hydrocarbon data. This is consistent with other reported observations of gas turbine data. NO_x variations are usually more consistent than either NO or NO_2. This may be due to sampling problems as previously noted in Section 1.2.5. A further variation is noted in the NO/NO_2 ratios at idle power especially in the smaller engine.

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USAF TURBINE ENGINE EMISSIONS INVENTORY USAF CONTRACT F29601-75-C-0046
ENGINE MODEL SUMMARY REPORT

ENGINE MODEL : J69-T25 TEST LOCATION : TELEDYNE,NEO ENGINE 1, PAGE 1

***** CATEGORY B TESTS ONLY *****

EXHAUST MASS EMISSION INDICES :

PARAM	TEST MODE	# / 1000# FUEL NO. OBS	MAX VALUE	MIN VALUE	MEAN	STND DEV	% COEF VAR	# / HR NO. OBS	MAX VALUE	MIN VALUE	MEAN	STND DEV	% COEF VAR
THC	IDLE	10	35.57	6.86	19.86	10.421	52.48	10	8.18	1.51	4.62	2.437	52.71
	INTERMED. 1	2	12.38	7.57	9.97	3.401	34.10	2	3.59	2.16	2.87	1.011	35.17
	INTERMED. 2	2	5.95	2.21	4.08	2.645	64.82	2	3.09	1.18	2.13	1.351	63.26
	NORMAL	10	1.87	0.59	1.29	0.497	38.60	10	1.23	0.42	0.89	0.316	35.62
	MILITARY	10	0.75	0.24	0.49	0.156	31.50	10	0.79	0.26	0.54	0.165	30.58
CO	IDLE	10	161.45	103.83	126.44	21.972	17.38	10	37.9	23.9	29.3	5.25	1.79
	INTERMED. 1	2	98.61	97.10	97.85	1.068	1.09	2	28.6	27.7	28.2	0.64	0.23
	INTERMED. 2	2	64.11	56.40	60.25	5.452	9.05	2	34.3	29.3	31.8	3.54	1.11
	NORMAL	10	56.27	36.50	48.72	5.655	11.61	10	37.7	30.3	33.8	2.55	0.75
	MILITARY	10	33.39	28.25	31.02	1.601	5.16	10	36.8	30.6	34.0	1.92	0.57
NOX	IDLE	9	1.80	1.27	1.53	0.186	12.10	9	0.41	0.29	0.36	0.042	11.86
	INTERMED. 1	2	2.12	1.98	2.05	0.099	4.83	2	0.60	0.58	0.59	0.014	2.40
	INTERMED. 2	2	2.79	2.55	2.67	0.170	6.36	2	1.45	1.37	1.41	0.057	4.01
	NORMAL	9	3.31	1.67	2.68	0.534	19.96	9	2.82	1.10	1.91	0.568	29.68
	MILITARY	9	4.15	2.66	3.60	0.520	14.47	9	4.50	2.88	3.95	0.561	14.18
NO	IDLE	10	1.81	0.04	0.41	0.578	139.70	10	0.42	0.01	0.10	0.134	139.69
	INTERMED. 1	2	0.22	0.14	0.18	0.057	31.43	2	0.06	0.04	0.05	0.014	28.28
	INTERMED. 2	2	1.12	0.96	1.04	0.113	10.88	2	0.58	0.51	0.54	0.049	9.08
	NORMAL	10	2.91	1.01	1.63	0.555	34.10	10	1.92	0.67	1.15	0.412	35.98
	MILITARY	10	3.81	2.15	2.63	0.469	17.84	10	4.04	2.34	2.87	0.485	16.88
NO2	IDLE	9	1.70	0.39	1.27	0.431	33.84	9	0.39	0.09	0.30	0.100	33.88
	INTERMED. 1	2	1.90	1.85	1.87	0.035	1.89	2	0.54	0.54	0.54	0.000	0.00
	INTERMED. 2	2	1.68	1.59	1.63	0.064	3.89	2	0.87	0.85	0.86	0.014	1.64
	NORMAL	9	1.64	0.41	1.19	0.478	40.12	9	1.35	0.26	0.85	0.380	44.46
	MILITARY	9	1.57	0.31	1.10	0.552	50.19	9	1.76	0.35	1.21	0.603	50.01
SOX	IDLE	0						10	0.48	0.18	0.33	0.140	41.65
	INTERMED. 1	0						2	0.58	0.57	0.57	0.007	1.23
	INTERMED. 2	0						2	1.07	1.04	1.05	0.021	2.01
	NORMAL	0						10	1.74	0.53	1.03	0.492	47.70
	MILITARY	0						10	2.24	0.88	1.58	0.650	41.20

Figure 3-1 Model Summary Sample Report

4.0 DATA ANALYSIS

4.1 ANALYSIS OF EMISSION INDEX AND SMOKE NUMBER VS. THRUST

For each engine type and model, individual plots of Smoke Number, Carbon Monoxide Emission Index, Total Hydrocarbon Emission Index and Nitrogen Oxide Emission Index versus Power Setting are presented as Figures 4-1 through 4-84 The Emission Indices are in units of pounds of pollutant per thousand pounds of fuel burned and the Power Setting is represented as Thrust (pounds), Engine Pressure Ratio or Horsepower.

Plotting coordinates were determined as the mean power setting and mean emission index or smoke number at each test mode on Categroy B tests. To provide an estimate of the scatter in the data, the range values around the mean coordinate are also plotted. The range was selected as a better measure of the scatter than the standard deviation due to the limited number of engines tested in each model category. In order to provide a comparison between the abbreviated sampling method of Category B tests and the 13-point sampling method of Category A tests, the A test points are also plotted. Only Category A tests were conducted on the TF39 engines, so the plotting coordinates are the mean of the 'A' test power setting and emission indices. For F100-PW100 engines, the 'S' tests conducted on this engine were also plotted. The 'S' tests were special tests to measure the net emissions from the test cell when water cooling was being used. The TF34-DEV and the T700 engines each had two Category A tests conducted on them using two fuels: JP4 and JP5.

The plots hold no surprises in that all trends are typical of gas turbine engines. The hydrocarbon emission index varies over three to four decades, decreasing with increasing power setting up to full military power. Erroneous hydrocarbon data were verified in the tests of the J79-15, T56-A7B, J57-19, J57-P21, J57-43, TF30-P3, TF30-P7, TF30-P100 and TF33-P7 engines. The erroneous data were caused by leakage of glycol coolant into the gas sample line of the rake probes. These bad data are all Category B test data measured using rake probes, and they can be seen to form a population considerably different from the Category A data (measured with a different probe).

The carbon monoxide index decreases with increasing power setting up to full military power. The range of CO emission index is two or three decades. Total oxides of nitrogen increase with power setting up through military power. The usual NO_x emission index at full power is approximately five times the emission index at idle. The smoke number increases with power setting for all the engines tested except the J69 engine which had the highest smoke number at idle. The J85-5, J60, TF39 and TF34 engines all had smoke numbers under 20 at all test modes.

4.2 VARIATION OF EMISSION INDEX AND CO_2 CONCENTRATION ACROSS EXHAUST PLANE

To define the representativeness of the 13-point Category A tests, computer plots of emission index at each sample point versus probe position for carbon monoxide, total hydrocarbons, nitrogen oxides and smoke number were developed. Additionally, to characterize the shape of the exhaust plume, plots of carbon dioxide (%) at each sample point versus probe position were developed. Figures 4-85 through 4-90 are the plots of Emission Index, Smoke Number and CO_2 concentration across the exhaust plane as measured during one Category A test. Data for J69, J57, TF30, J79, J85 and TF39 engines are presented as examples.

The plots presented have the X-axis divided into the respective $+30^{\circ}$ and -30° traverses. Sample points 1 through 12 are positioned at the centers of equal areas while point 13 represents the center of the exhaust plume. The center point although not required for the calculation of emission rate since it is not a "center of equal area" is very useful in studies of the distribution of exhaust constituents. Capital letter I's are used at the upper and lower margins of the plots to indicate the boundaries of the area represented by each sample point. The spacing between the boundaries decreases as one moves out from the center, but the areas represented between the boundaries are equal.

The emission index at each point was calculated by the method of ARP 1256 from the exhaust concentrations measured at each sample point. The emission index is therefore determined by the carbon balance at each point and is essentially a ratio of the pollutant to CO_2 at each sample point.

If the exhaust gases were well mixed over the exhaust plane the emission index (which is a ratio of the pollutant concentration to the CO_2 concentration) would be constant across any exhaust diameter. Reference to the plots of emission index versus probe position shows that hydrocarbons and CO are poorly mixed with the CO_2 at all power settings for the majority of the engines tested. The oxides of nitrogen by comparison are very well mixed with the CO_2 and demonstrate profiles of constant emission index. When the NO_x emission index does not approximate a horizontal line, erroneous data are suspected. An example of such is the J79-15 NO_x plots on Figure 4-88. The steep gradient at the edges of the NO_x (and also the CO and THC plots) was caused by an erroneous CO_2 measurement. The error was traced to a misadjusted CO_2 analyzer. The CO_2 error was negligible at the higher concentration level but approximately 30% at the low concentration levels of the edge of the exhaust plume. This error is present only in the Category A test of the engine and though a marked distortion occurred to the emission index patterns, the average emission indices for the Category A test agreed well with the data of the five Category B tests also performed on this engine. Therefore these data were retained.

The degree to which a given sample point is representative of its assigned area can be determined from the plots of emission index, although this was not done as a part of this analysis. The plots were made some time after all the emissions tests were completed. Had similar plots been made at the beginning of the testing of each engine type, insight could be gained as to the most appropriate sampling points for each power setting. The replicate testing of the remaining engines of the type could then have been done with this benefit.

The plots of CO_2 distribution were examined for similarities and differences. Table 4-1 summarizes these CO_2 plume shapes and characterizes the engines by plume shape. Four plume shapes were selected which describe the plume patterns. The Group 1 pattern is flat across the exhaust plume. The Group 2 pattern is flat in the center with sharply sloping sides. The Group 3 pattern has a smooth peak and the Group 4 pattern is two-humped with a smooth depression in the center. The power mode codes used in this

table are those of Figures 4-1 through 4-84 and correspond to idle, intermediate and military thrust. The CO_2 plume pattern is closely related to engine type. The four engine types are turbojets, turbofans with either mixed exhaust or external fans and turboshaft engines (turboprop and helicopter engines). The turbojets all fall into Group 4 with the exception of the J85-5. The turbofan engines with external fans also fall into this group since their exhaust as sampled contained none of the fan air. Group 3 and Group 2 (which is really a special case of 3) contain the mixed turbofan engines. The T56 turboshaft engine had a flat CO_2 pattern at idle and a Group 3 pattern at the higher power setting.

The CO_2 plume pattern is of interest primarily as an indication of combustion zones. The CO_2 pattern of itself cannot be used to establish representative sampling points for emission tests. If the pollutant patterns followed the CO_2 pattern, then representative sampling could be done at just a few locations in the exhaust plane. However, the other pollutants do not follow the CO_2 distribution as was discussed above.

4.3 COMPARISON OF CATEGORY B AND CATEGORY A SAMPLING

Tables 4-2 through 4-5 are compilations of Category A and Category B at three power settings: Idle, Intermediate and Military. One table each compares the THC, CO, NO_x and Smoke for all the engines tested.

The data are tabulated on the Category A and Category B tests at each power setting. Two engine models had two Category A engines tested: the J60 and T56. For all other engine models, only one engine per model was tested in Category A. The mean, minimum and maximum levels found in the Category B tests are listed. Several Category B engines of each model type were tested. When the same engine tested in Category A was also tested in Category B, those test results are entered in the table under the Column marked B*. The comparisons have been further divided into those B tests using the four-point traverse and the B tests which used the rake probes.

Large differences between the Category A and Category B tests were found in the hydrocarbon data. These differences were caused by contamination of the rake probe by the leakage of glycol coolant into the gas sample line. Although the rake probes were repaired several times, sufficient leakage remained to cause erroneous data. The CO, NO_x and Smoke data were not affected by the glycol leaks.

Apart from this obvious case of the hydrocarbon data, large differences between engine tests remain between the Category A and Category B results for all the pollutant species. Some of the differences can be attributed to real differences between engines. In those cases where both Category A and Category B tests were conducted on the same engine, cause of the difference between the two types of tests is more easily assigned. Although some run to run variation can occur, the major cause of the difference between the A and B results is caused by the two sets of sampling points used for the two measurements. The Category A test used twelve sample points, three in each "quadrant" of the exhaust plane. The B test used four points on one quadrant with both sets of sample points located at centers of equal area. If three points were used for the B test instead of four, then the two tests might have been more comparable especially if there was good symmetry of the pollutant distribution. Comparing four points against three per quadrant introduces a variation due to the steepness of the edge pattern. The variation is compounded by poor pollutant symmetry. Reference to Figures 4-84 through 4-90 shows that both the THC and CO distributions can be much higher in some quadrants than others and indeed even the trend in emission index can reverse from one quadrant to another. Figure 4-87 illustrates these skewed CO and THC patterns. Since the CO and THC patterns are similar, one gives credence to the other eliminating suspicion of instrument or sample line biases. Sampling just one quadrant in such a situation produces a limited view of the pollutant distribution.

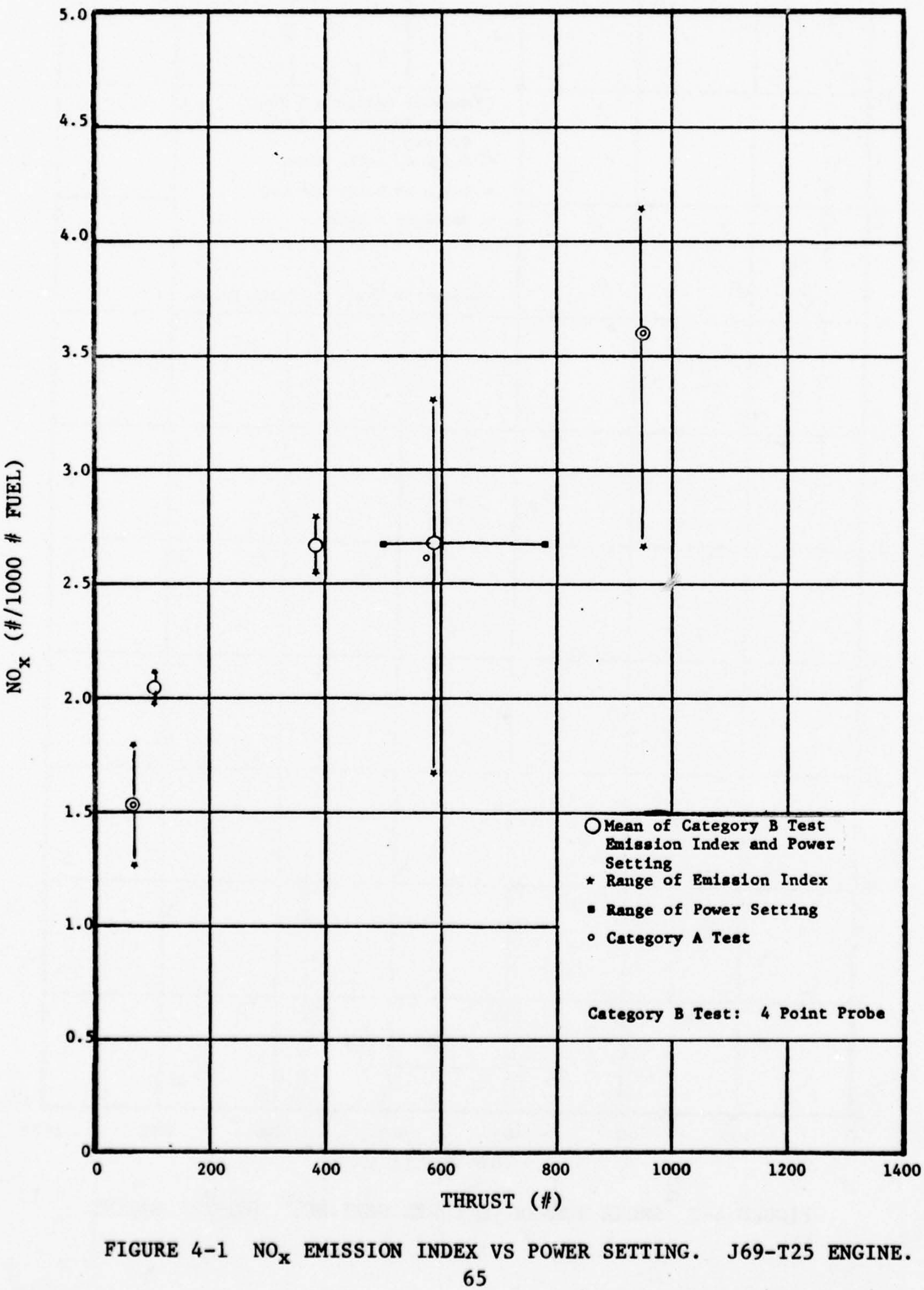


FIGURE 4-1 NO_x EMISSION INDEX VS POWER SETTING. J69-T25 ENGINE.

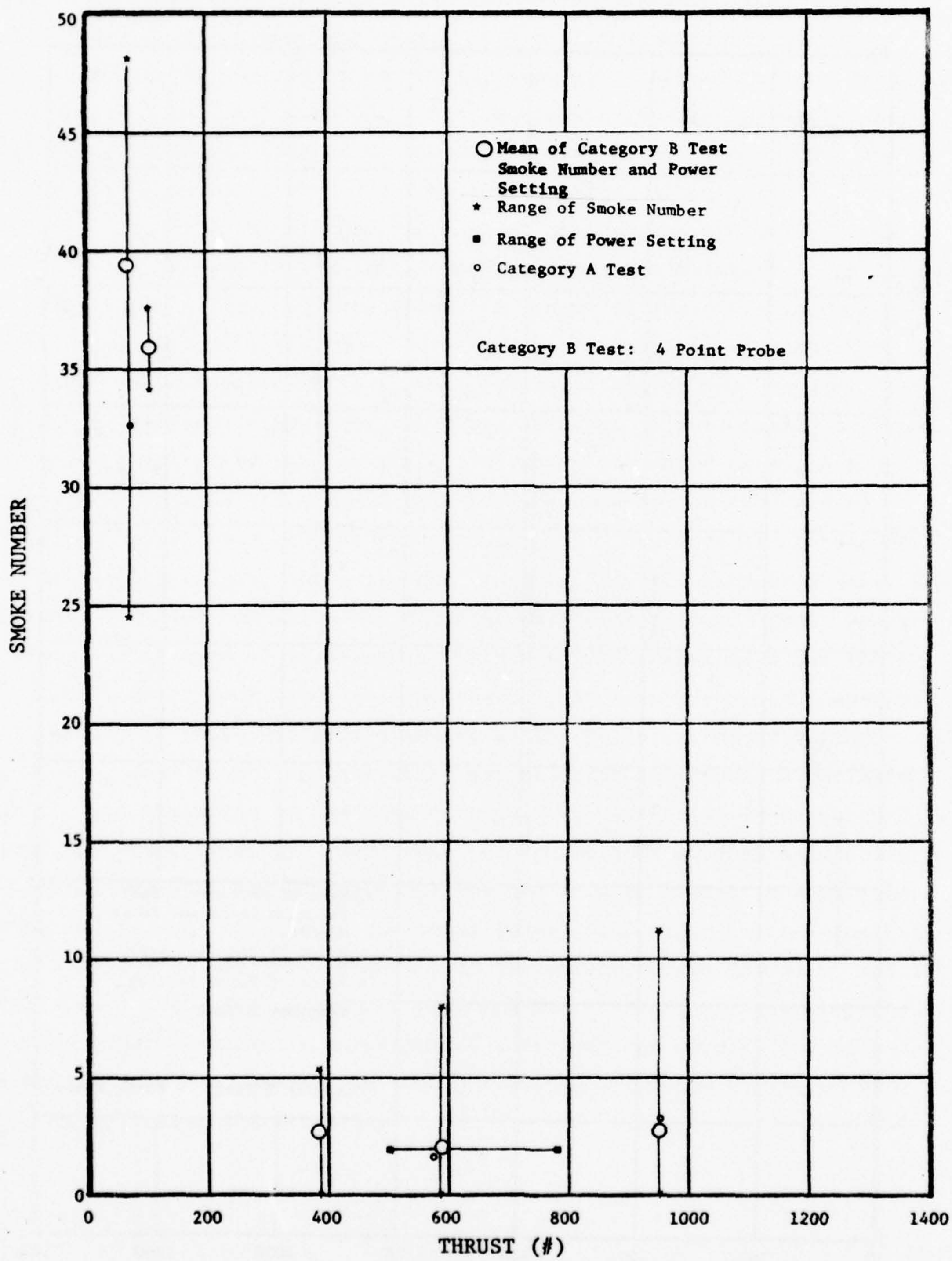


FIGURE 4-2 SMOKE NUMBER VS POWER SETTING. J69-T25 ENGINE.

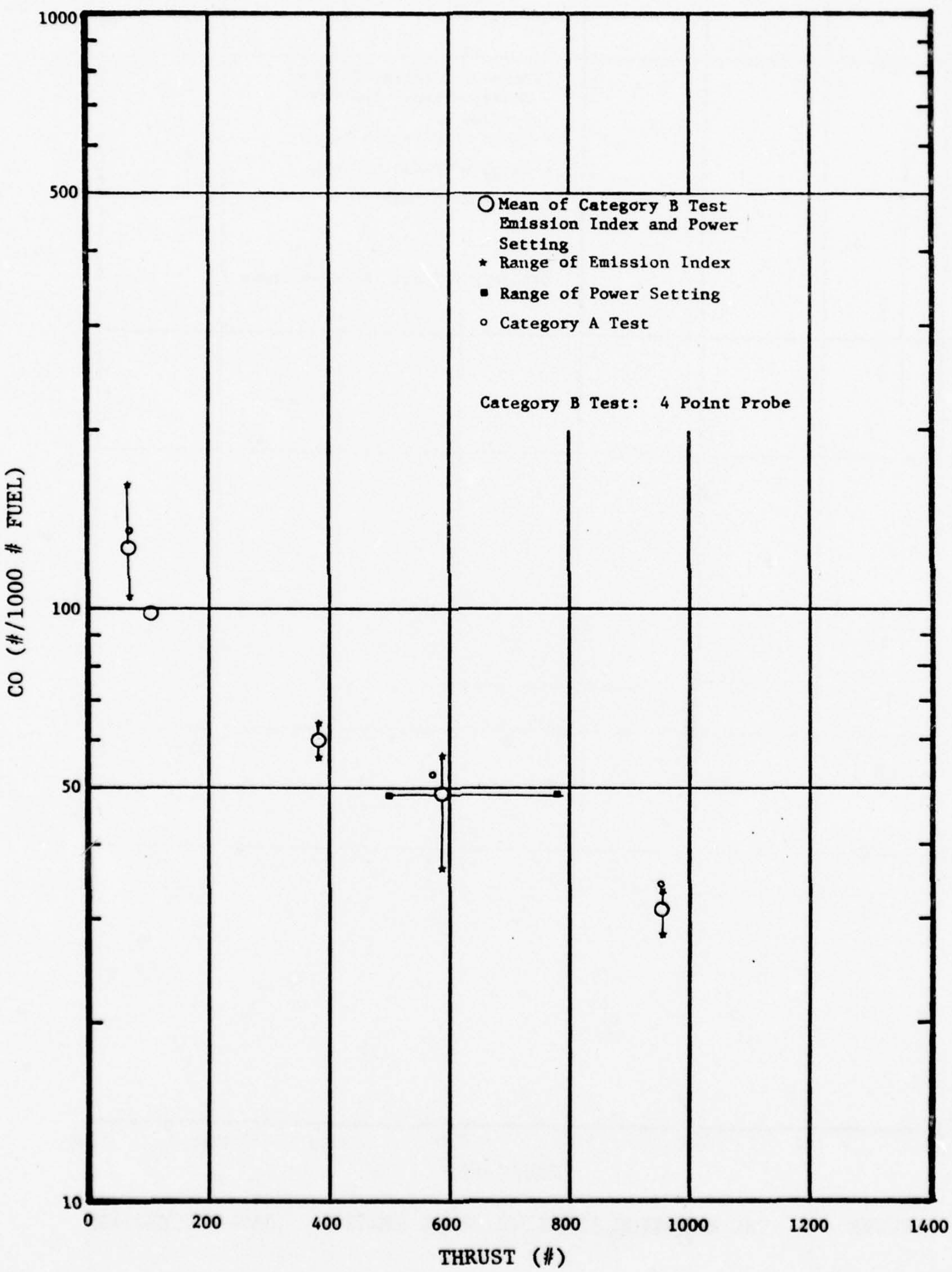


FIGURE 4-3 CO EMISSION INDEX VS POWER SETTING. J69-T25 ENGINE.

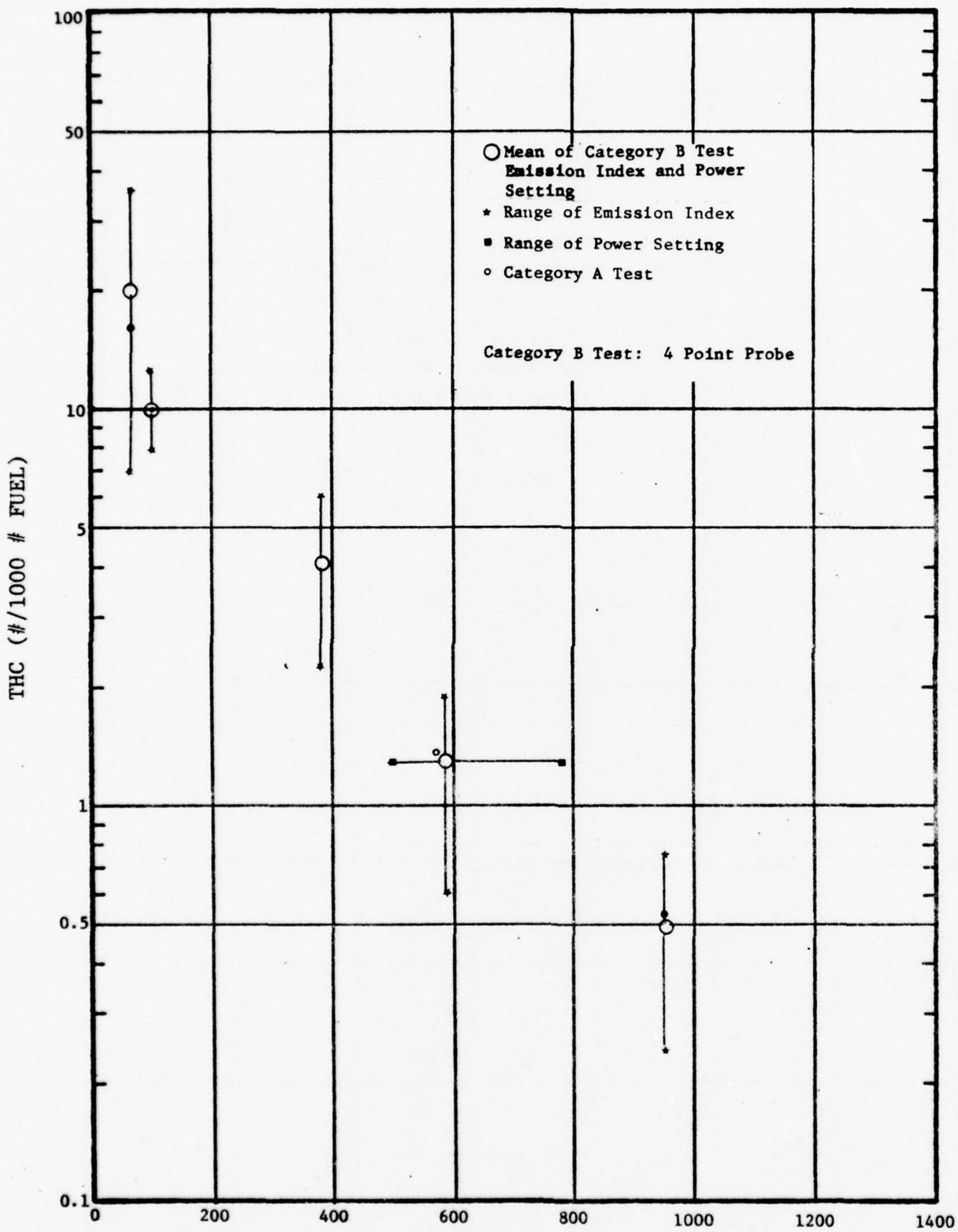


FIGURE 4-4 THC EMISSION INDEX VS POWER SETTING. J69-T25 ENGINE.

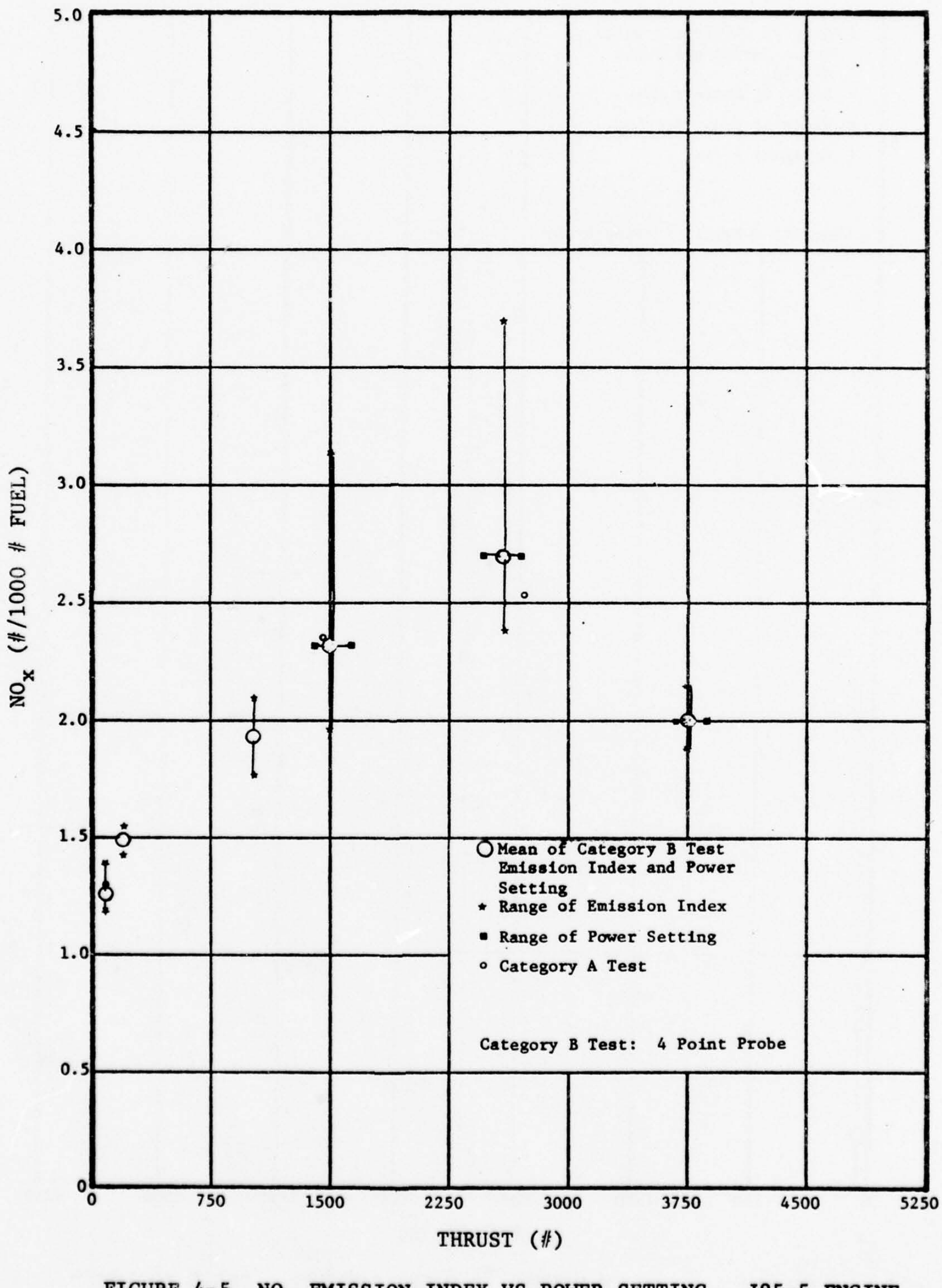


FIGURE 4-5 NO_x EMISSION INDEX VS POWER SETTING. J85-5 ENGINE.

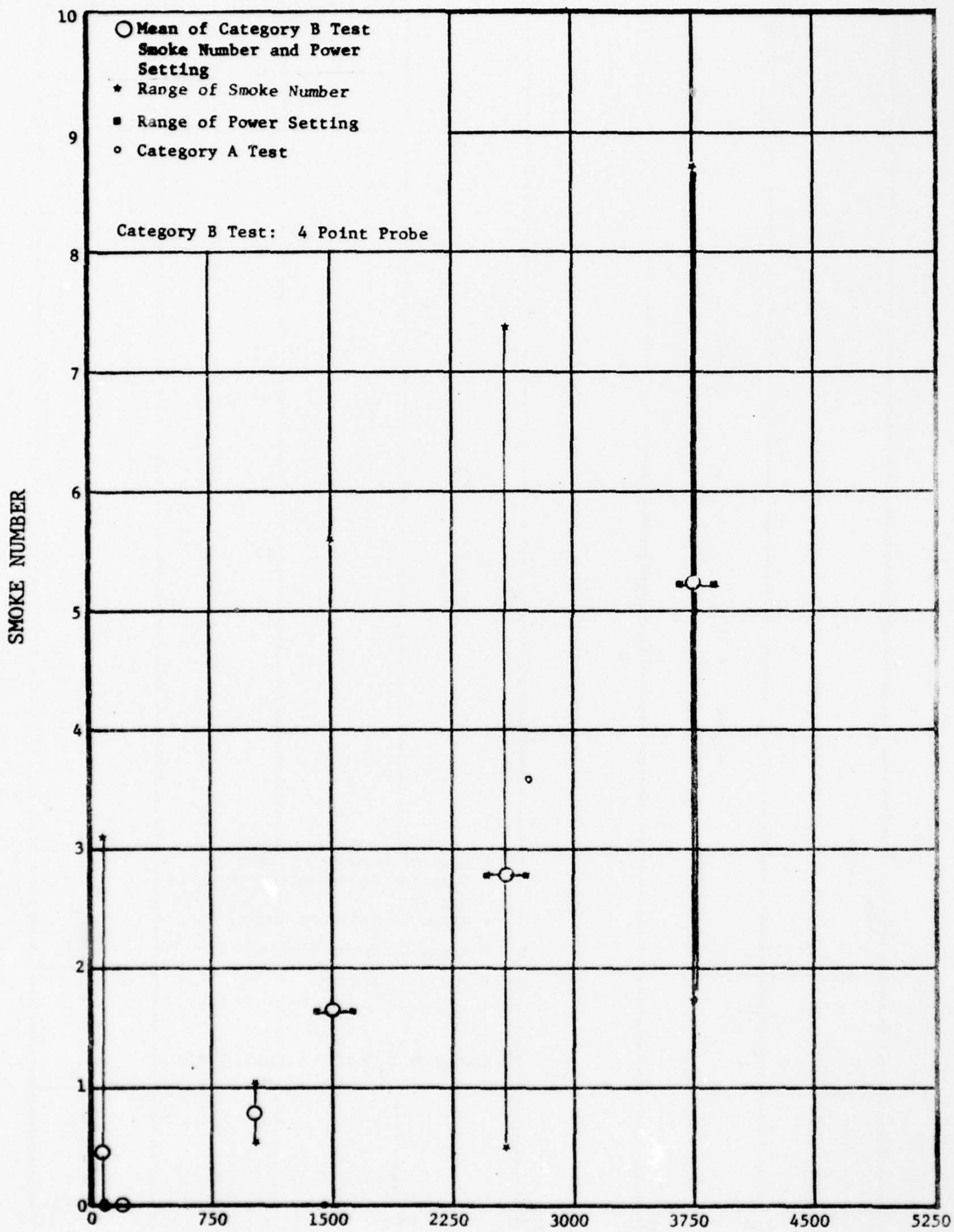


FIGURE 4-6 SMOKE NUMBER VS POWER SETTING. J85-5 ENGINE

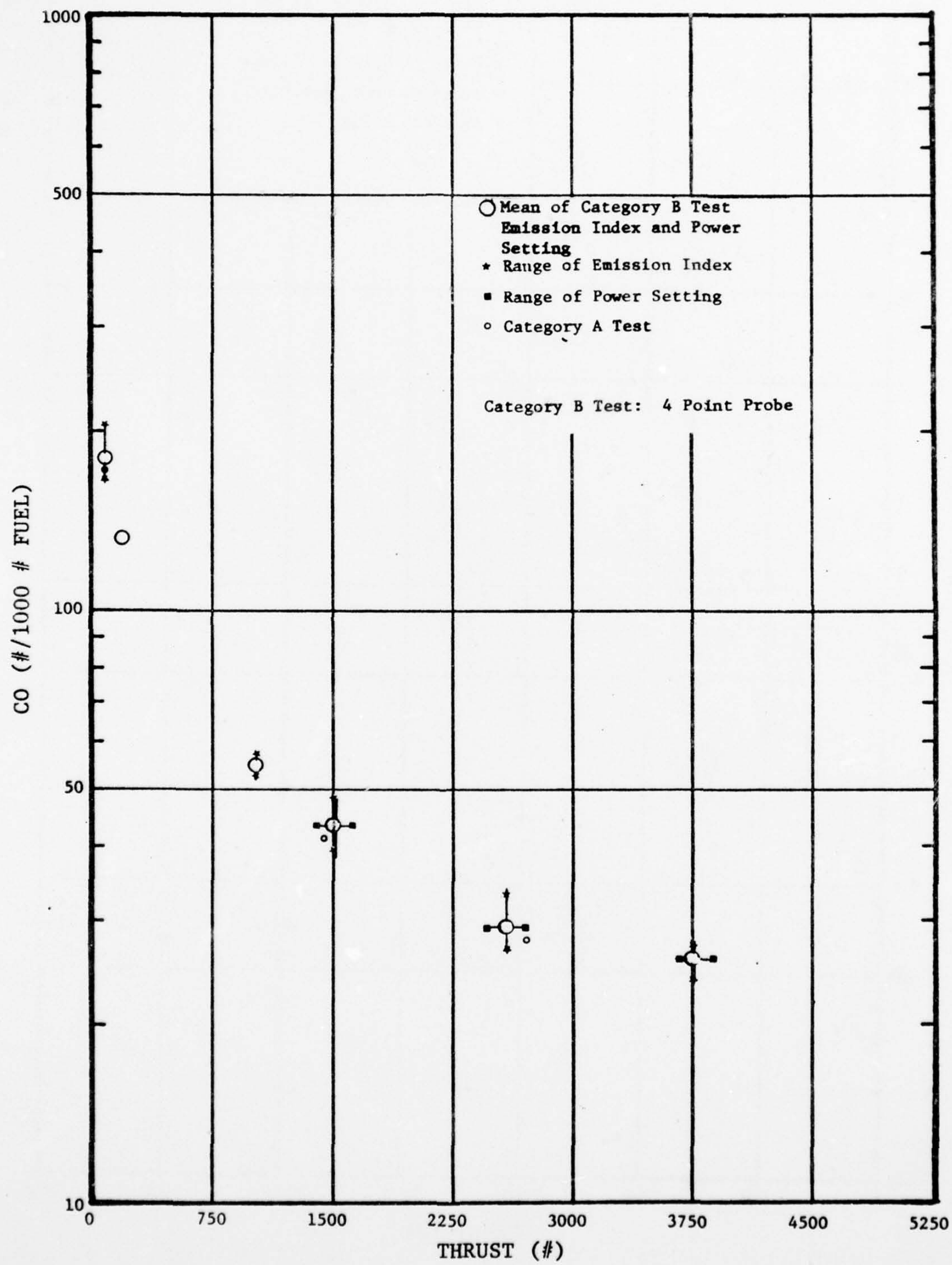


FIGURE 4-7 CO EMISSION INDEX VS POWER SETTING. J85-5 ENGINE

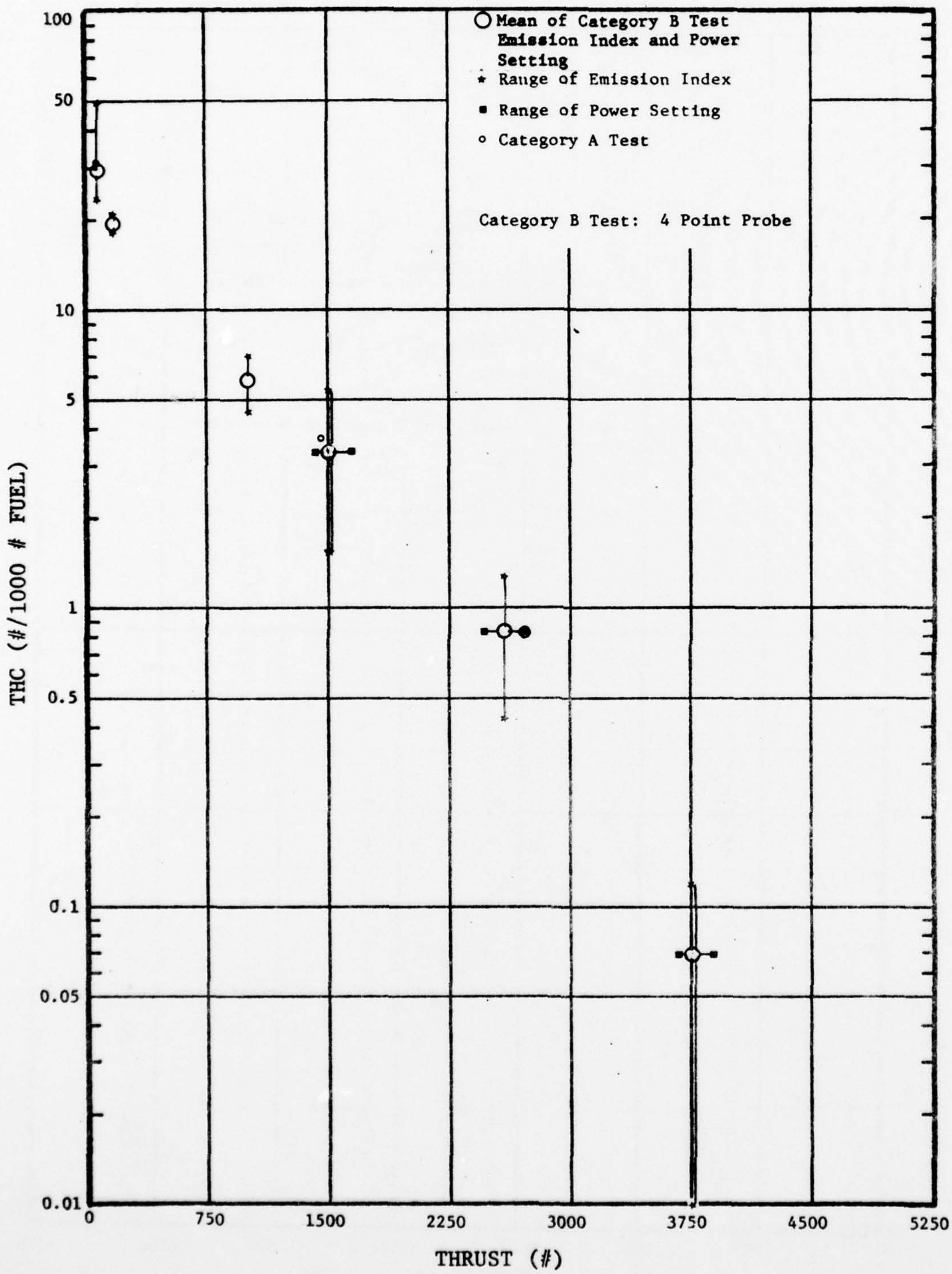


FIGURE 4-8 THC EMISSION INDEX VS POWER SETTING. J85-5 ENGINE.

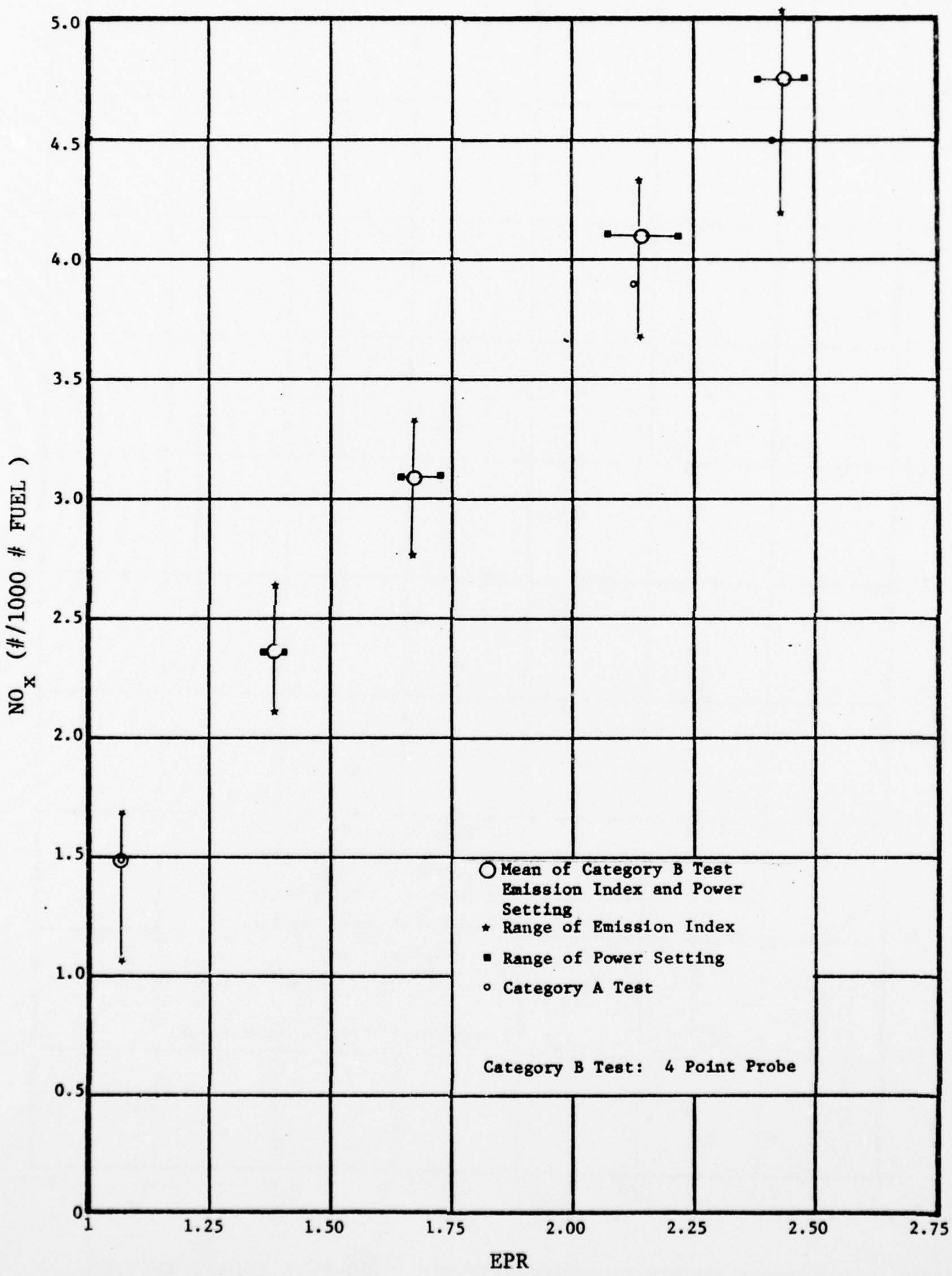


FIGURE 4-9 NO_x EMISSION INDEX VS POWER SETTING. J60-P5 & J60-P3 ENGINES

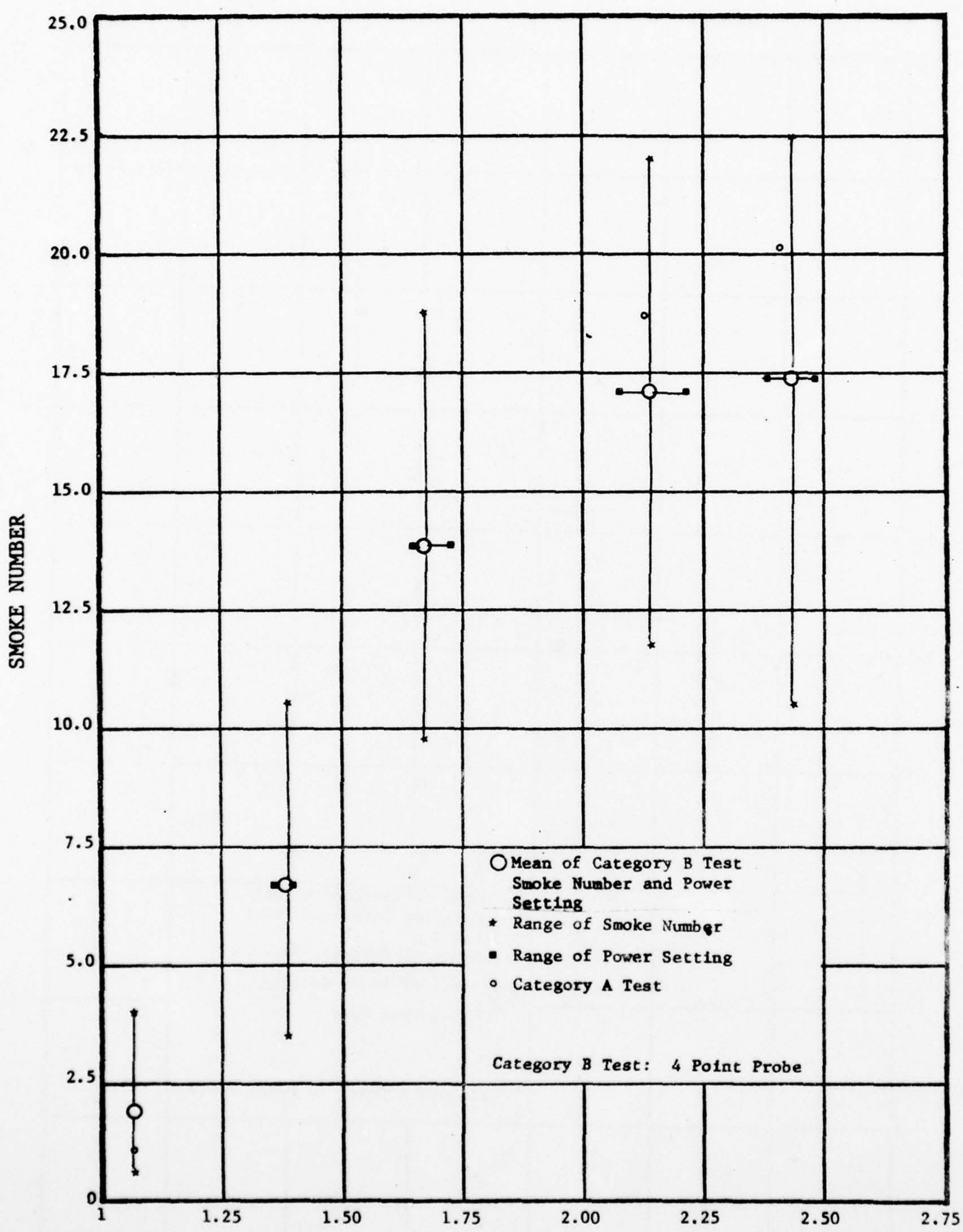


FIGURE 4-10 SMOKE NUMBER VS POWER SETTING. J60-P5 & J60-P3 ENGINES.

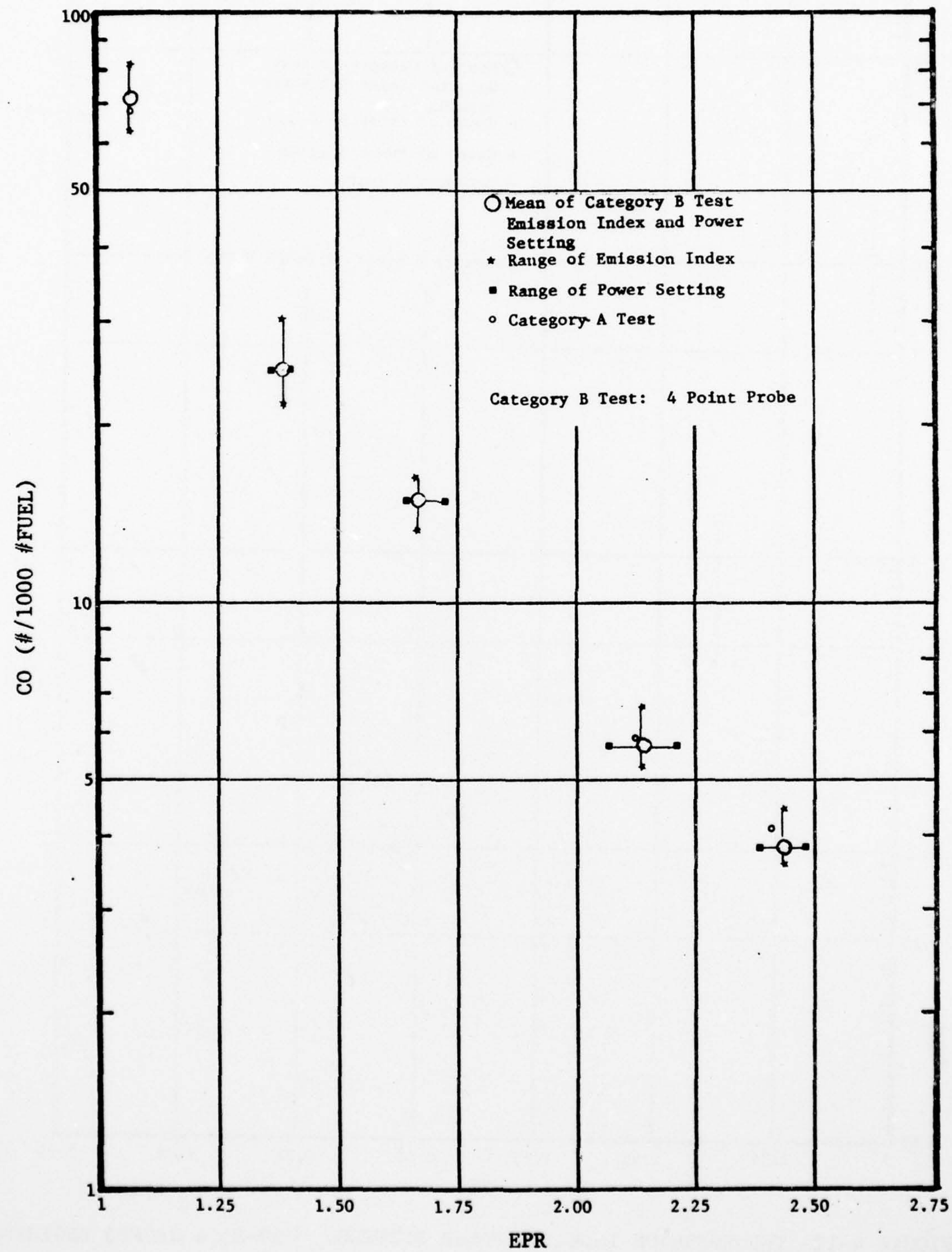


FIGURE 4-11 CO EMISSION INDEX VS POWER SETTING. J60-P5 & J60-P3 ENGINES.

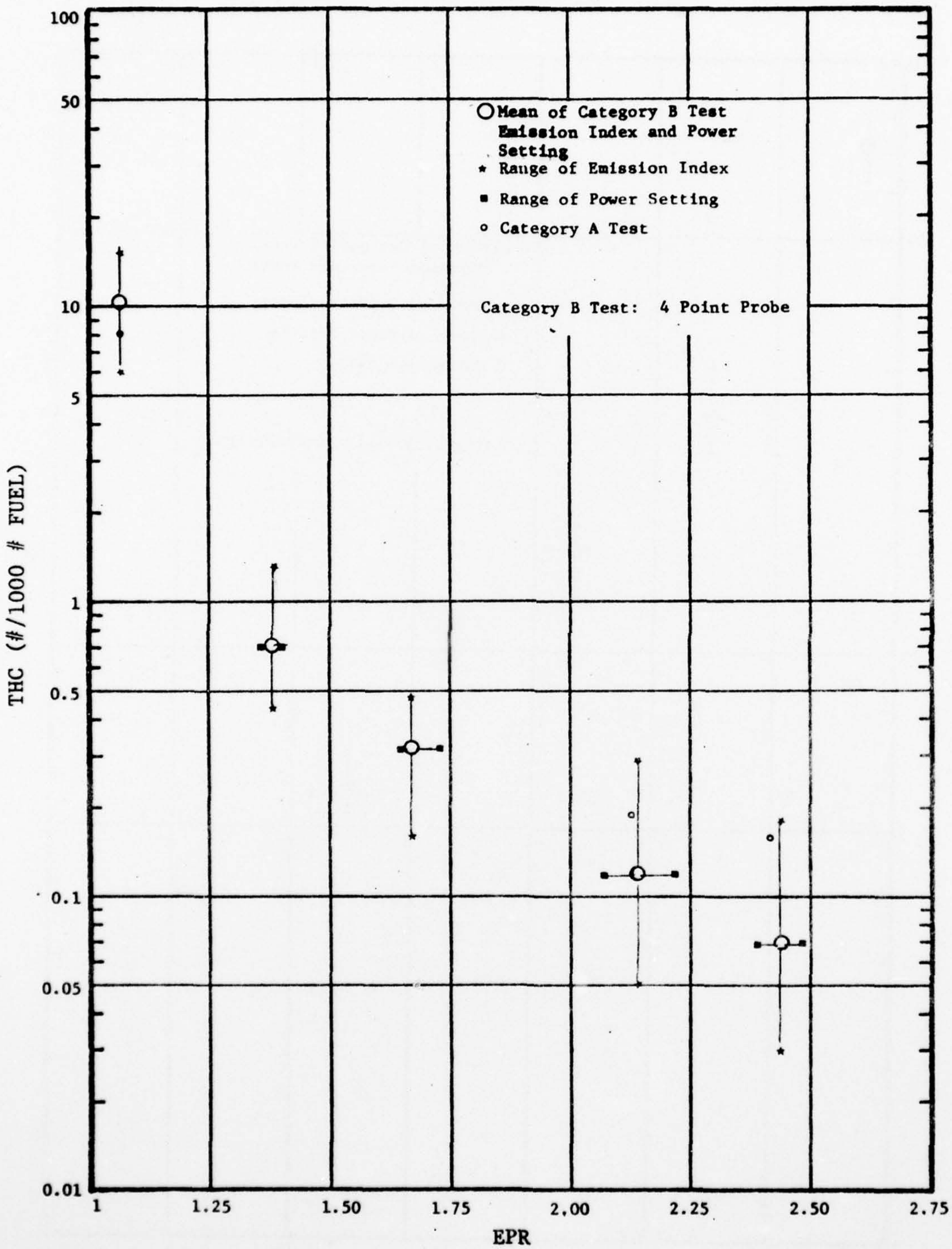


FIGURE 4-12 THC EMISSION INDEX VS POWER SETTING. J60-P5 & J60-P3 ENGINES.

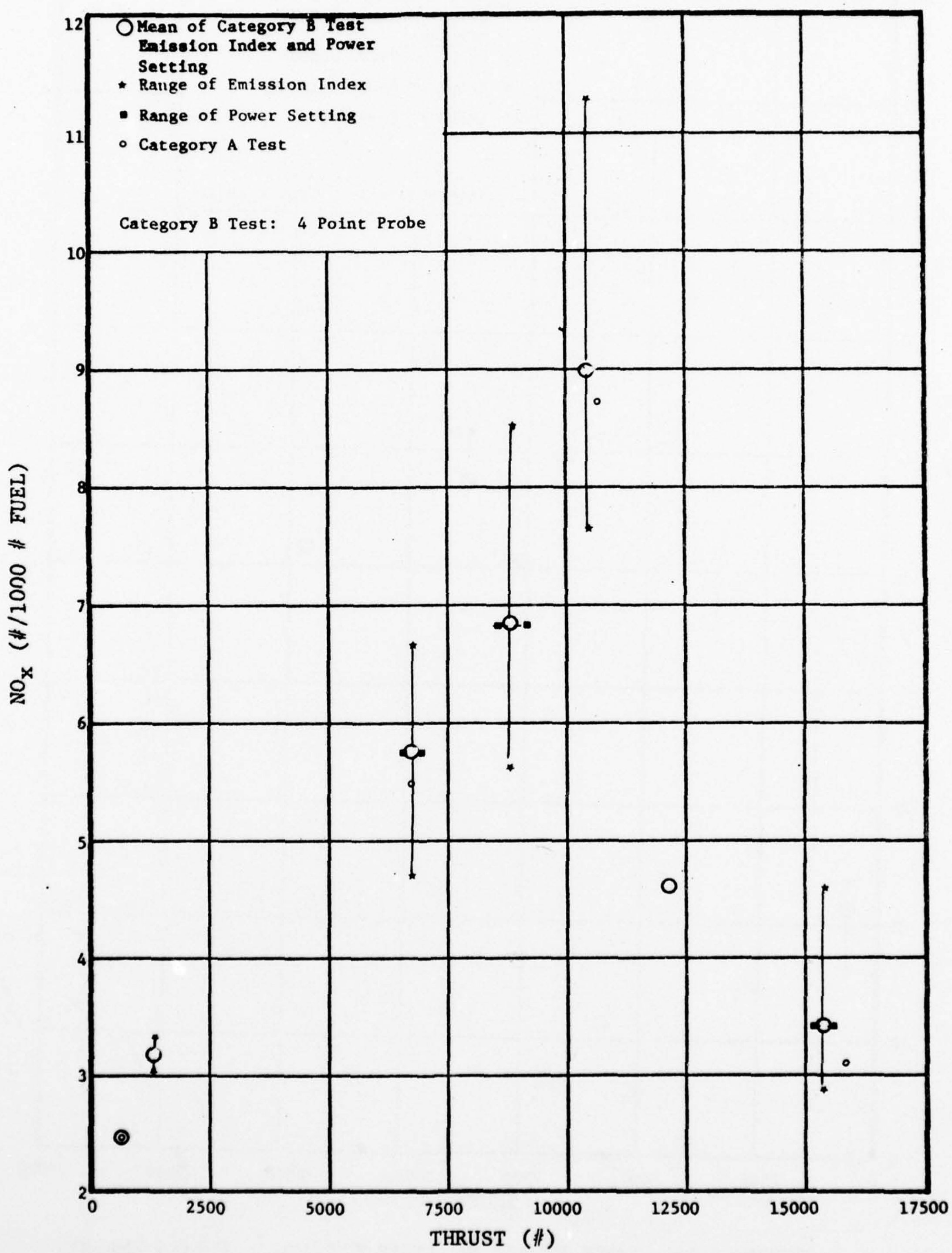


FIGURE 4-13 NO_x EMISSION INDEX VS POWER SETTING. J79-15 ENGINE.

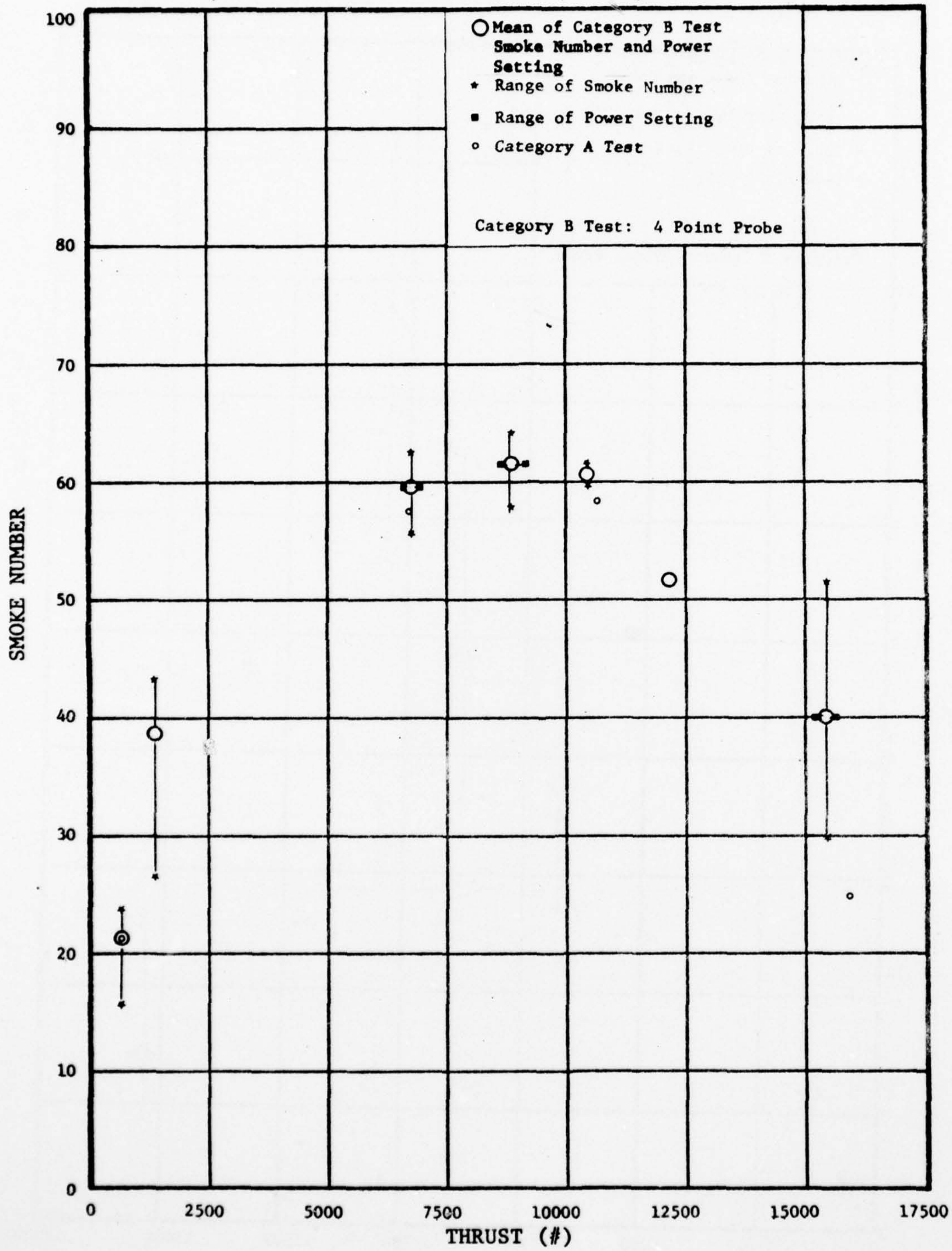


FIGURE 4-14 SMOKE NUMBER VS POWER SETTING. J79-15 ENGINE.

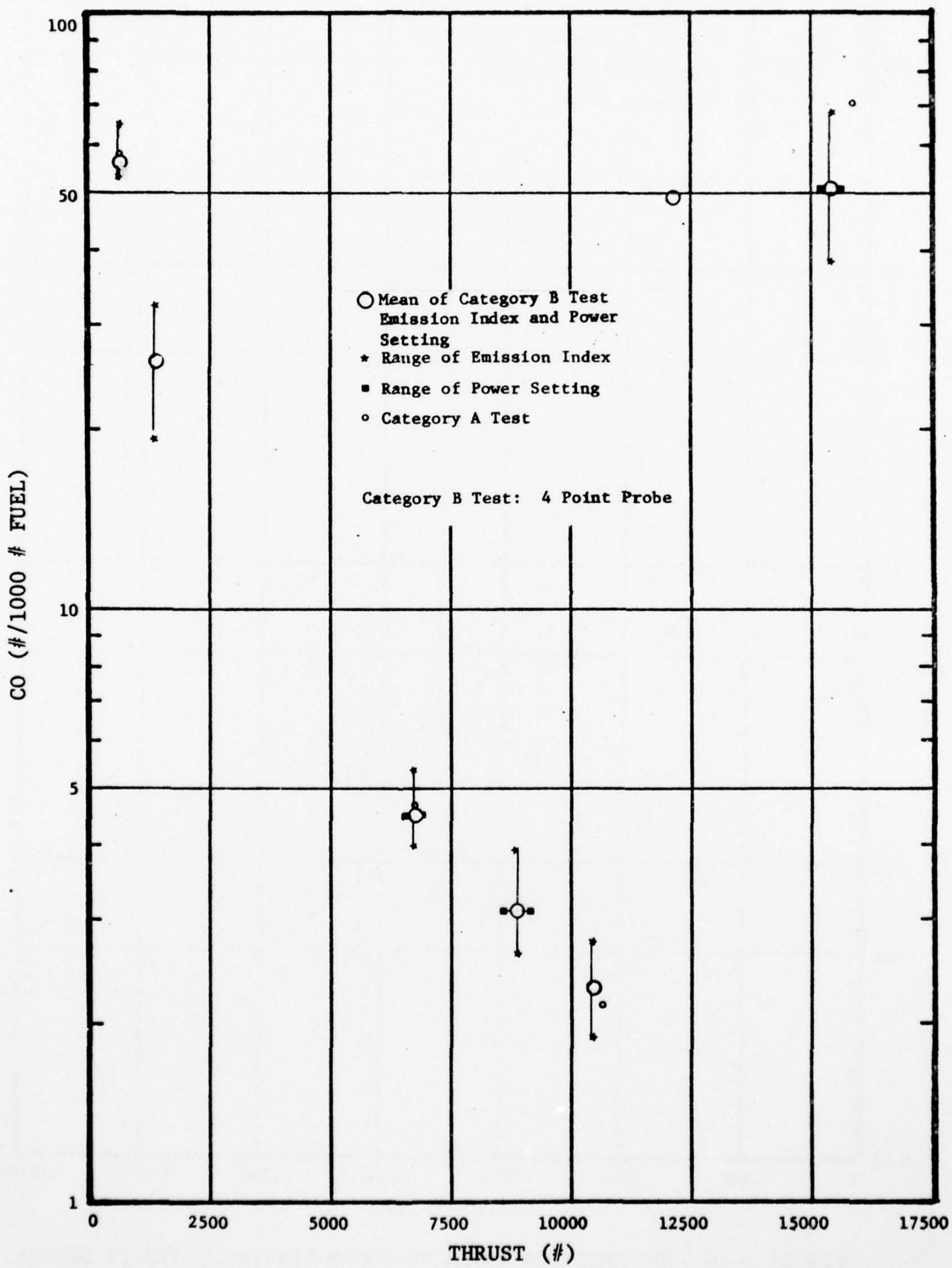


FIGURE 4-15 CO EMISSION INDEX VS POWER SETTING. J79-15 ENGINE.

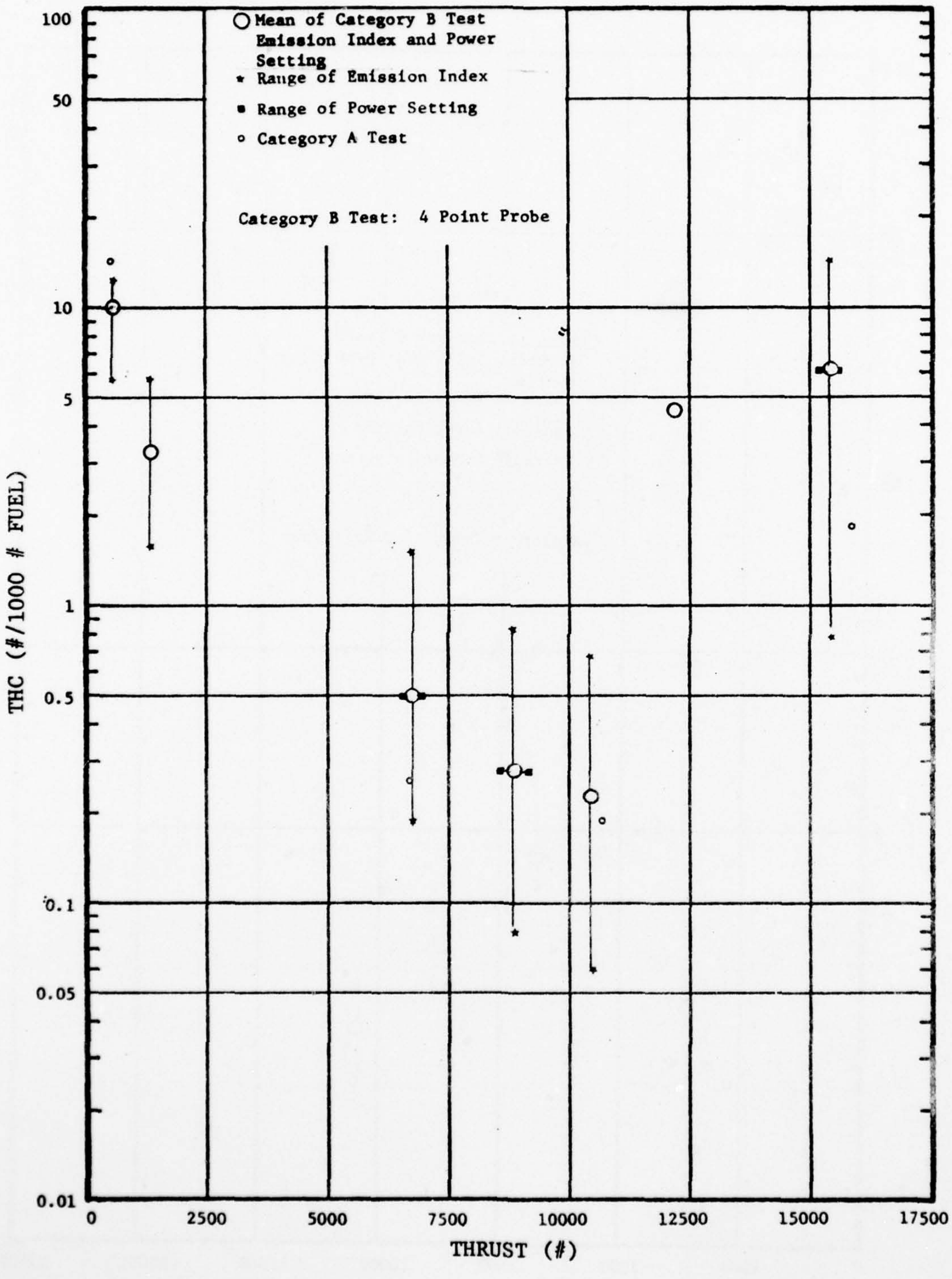


FIGURE 4-16 THC EMISSION INDEX VS POWER SETTING. J79-15 ENGINE

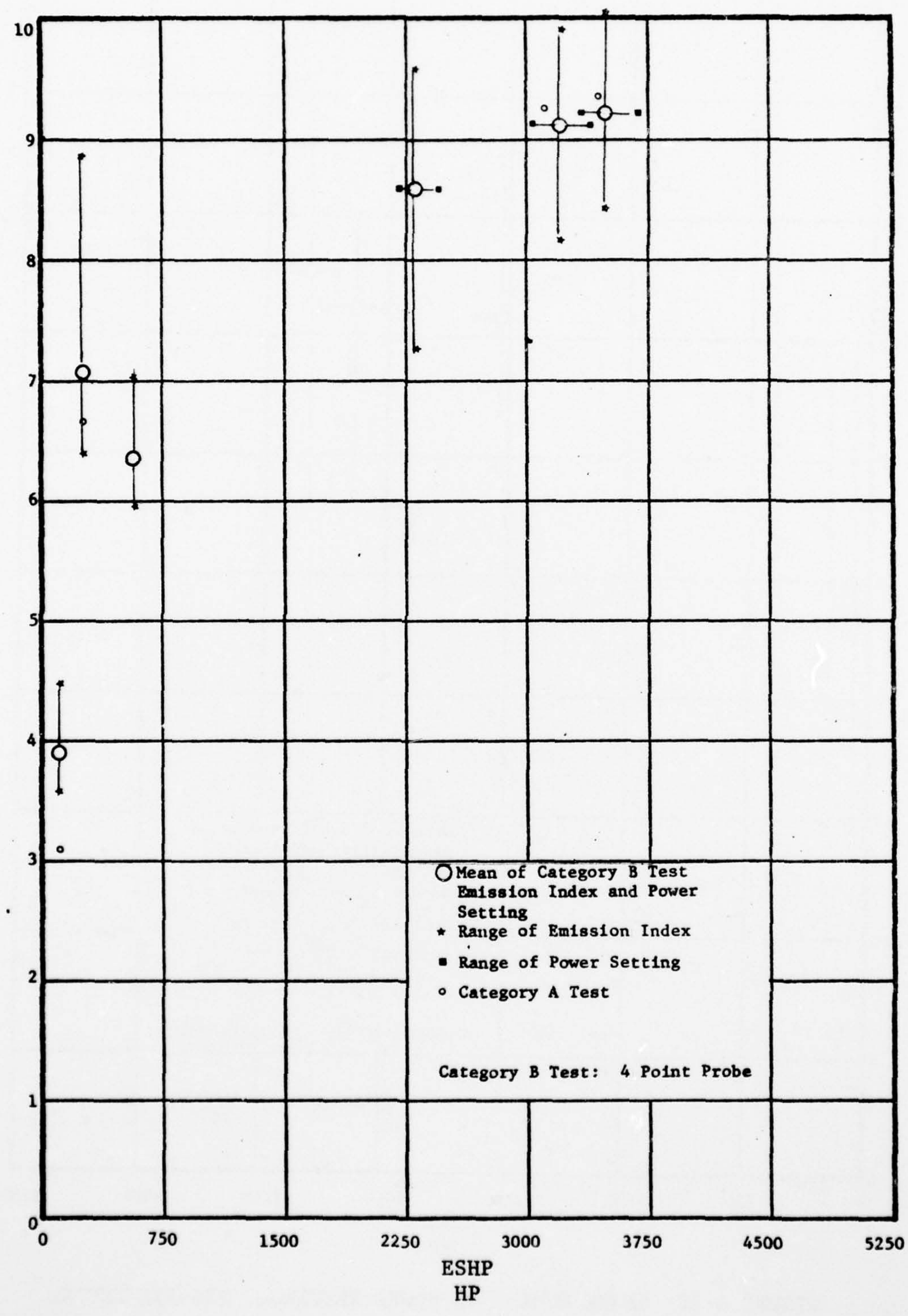


FIGURE 4-17 NO_x EMISSION INDEX VS POWER SETTING. T56-A7B ENGINE.

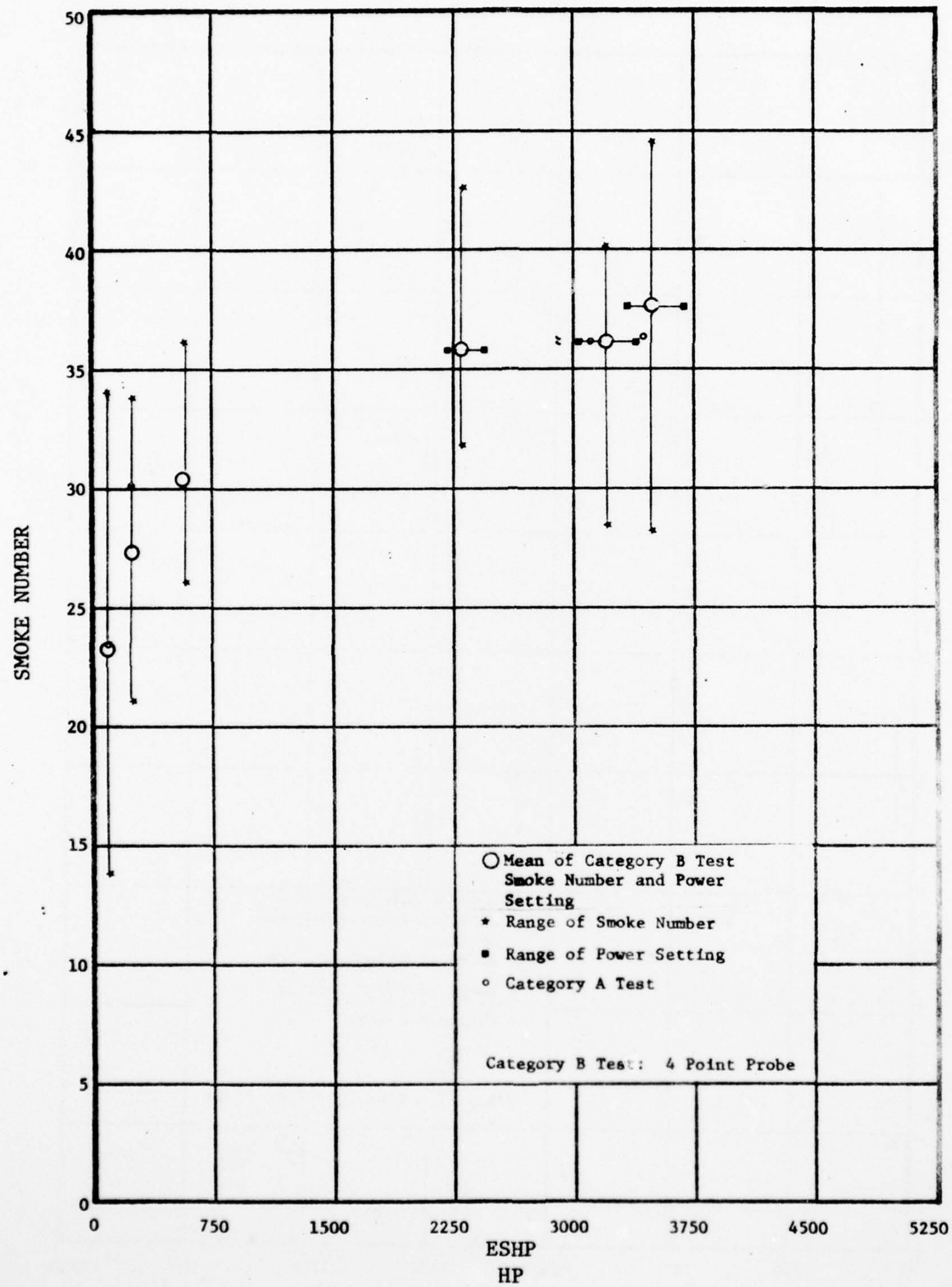


FIGURE 4-18 SMOKE NUMBER VS POWER SETTING. T56-A7B ENGINE

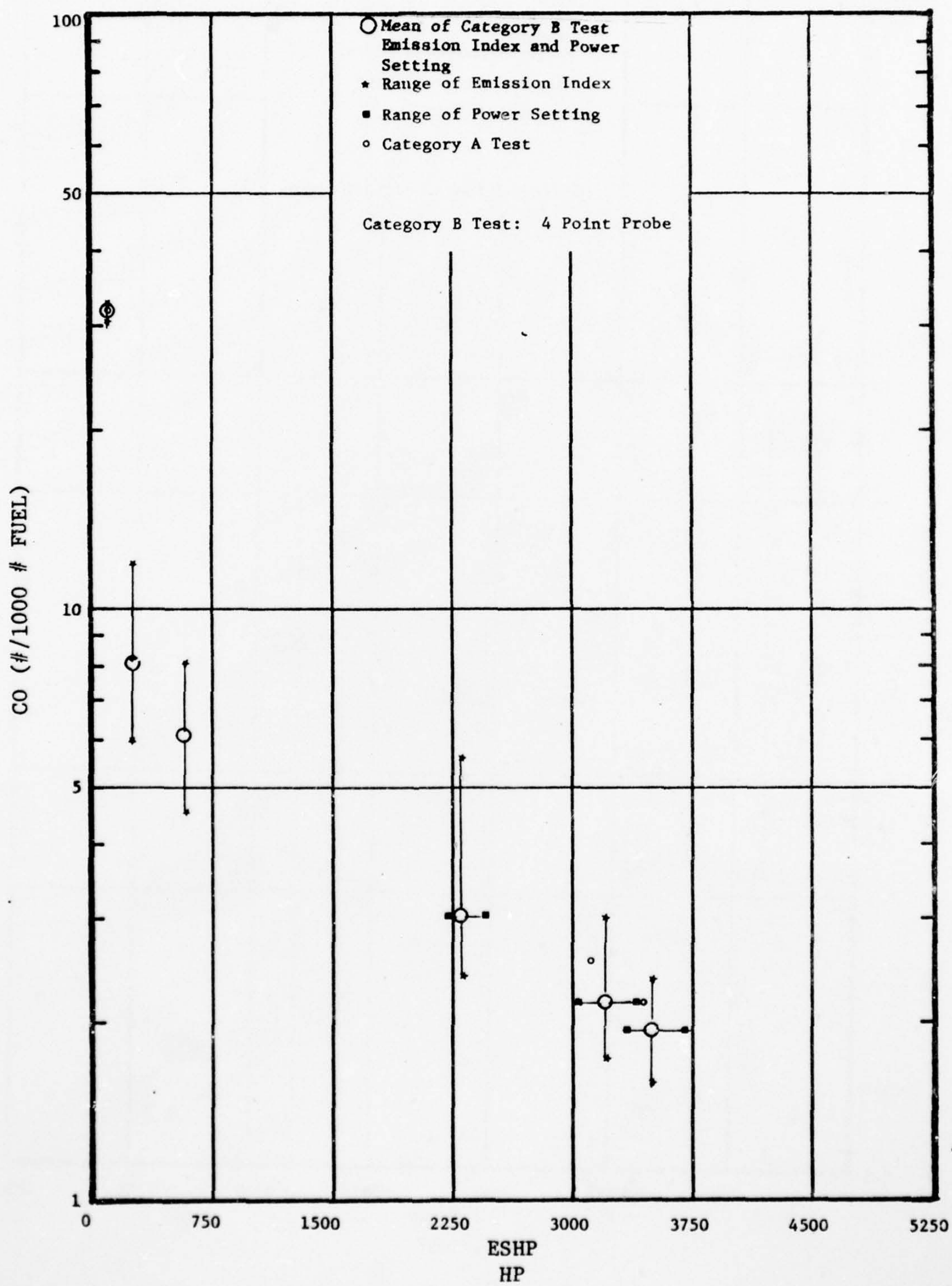


FIGURE 4-19 CO EMISSION INDEX VS POWER SETTING. T56-A7B ENGINE

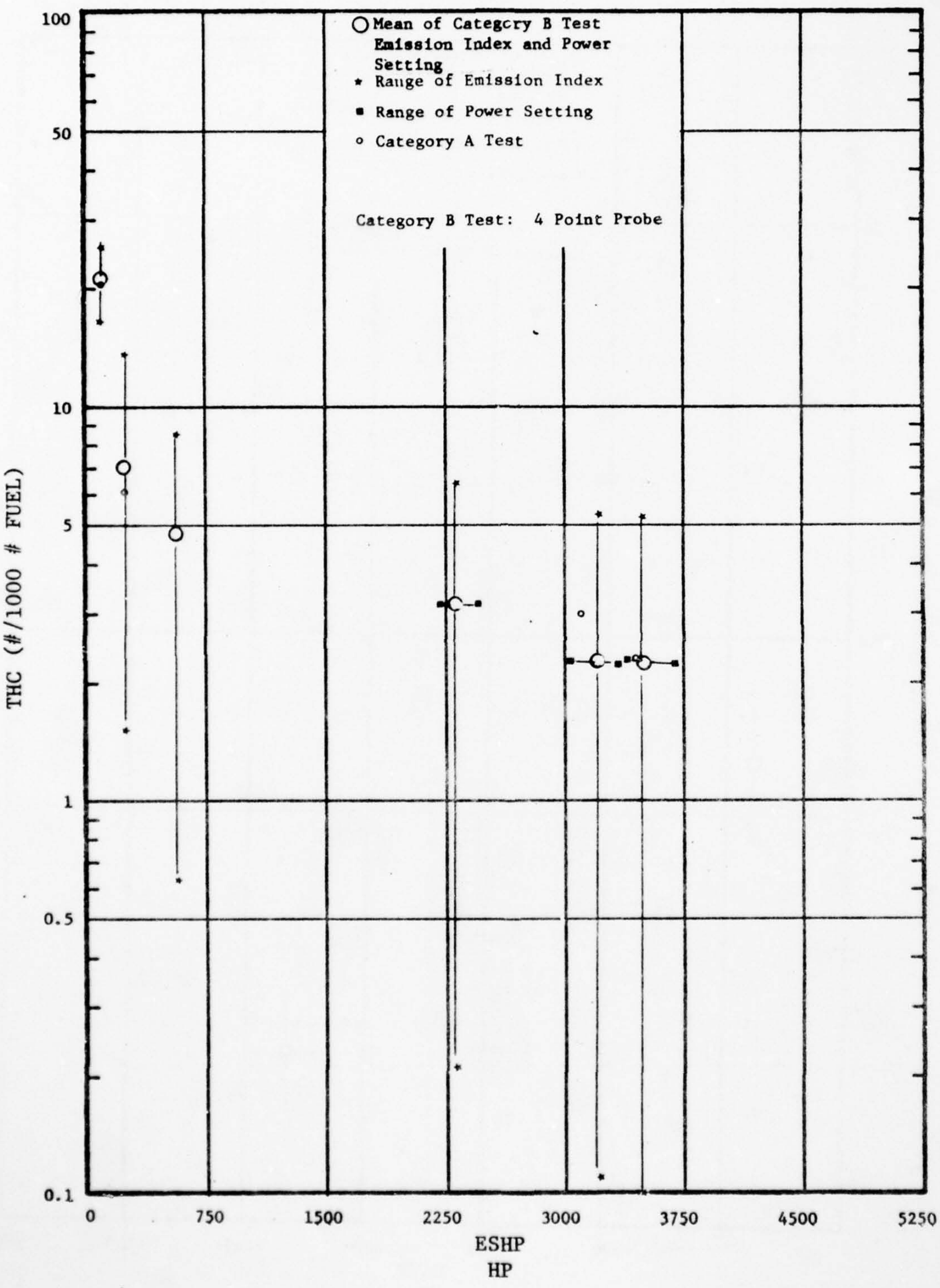
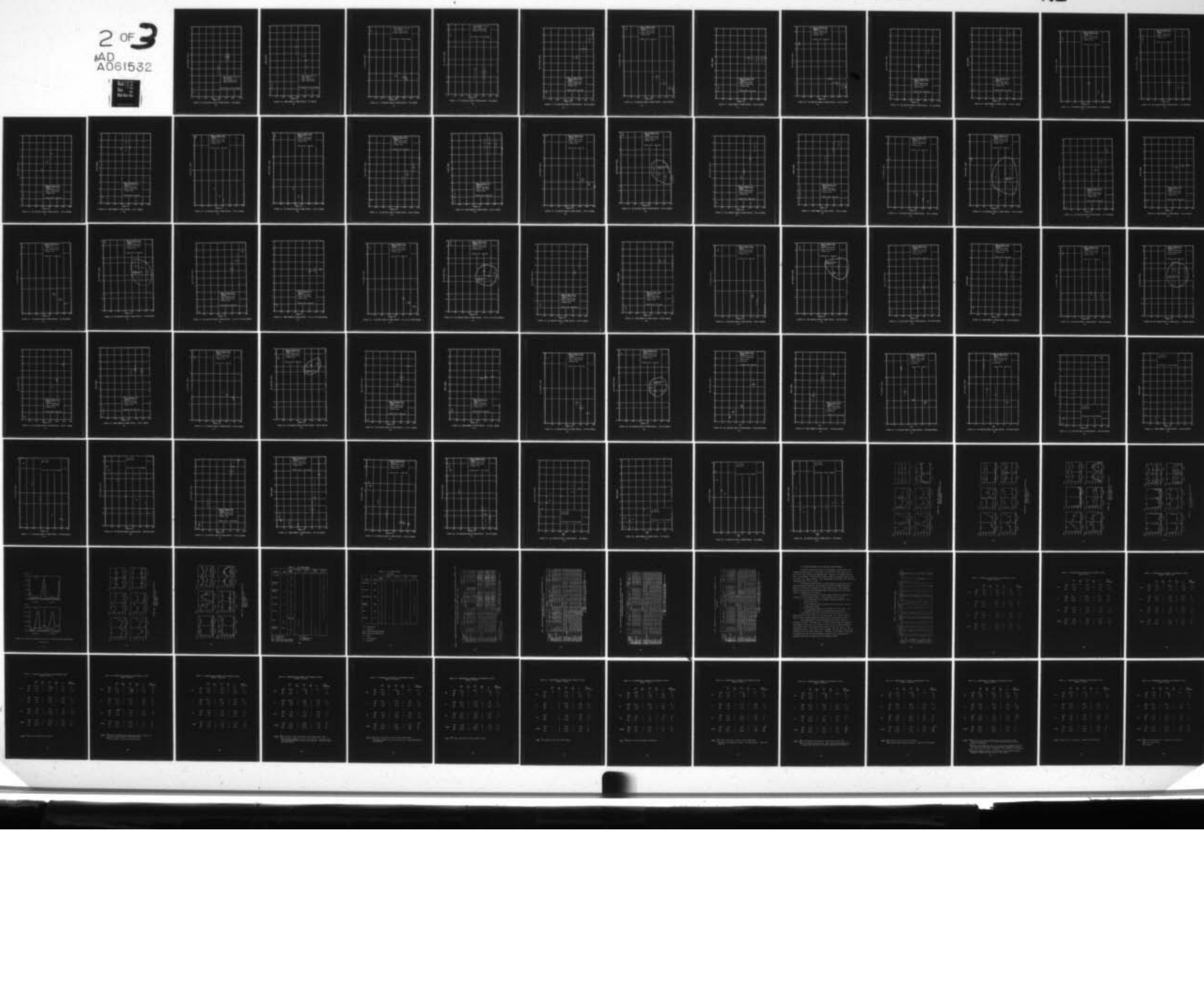


FIGURE 4-20 THC EMISSION INDEX VS POWER SETTING. T 56-A7B ENGINE

AD-A061 532 SCOTT ENVIRONMENTAL TECHNOLOGY INC PLUMSTEADVILLE PA F/G 21/5
AIR FORCE TURBINE ENGINE EMISSION SURVEY. UNITED STATES. VOLUME--ETC(U)
AUG 78 A F SOUZA, P S DALEY F29601-75-C-0046
UNCLASSIFIED SET-1492-50-0877-VOL-1 CEEDO-TR-78-34-VOL-1 NL

2 OF 3
AD
A061532



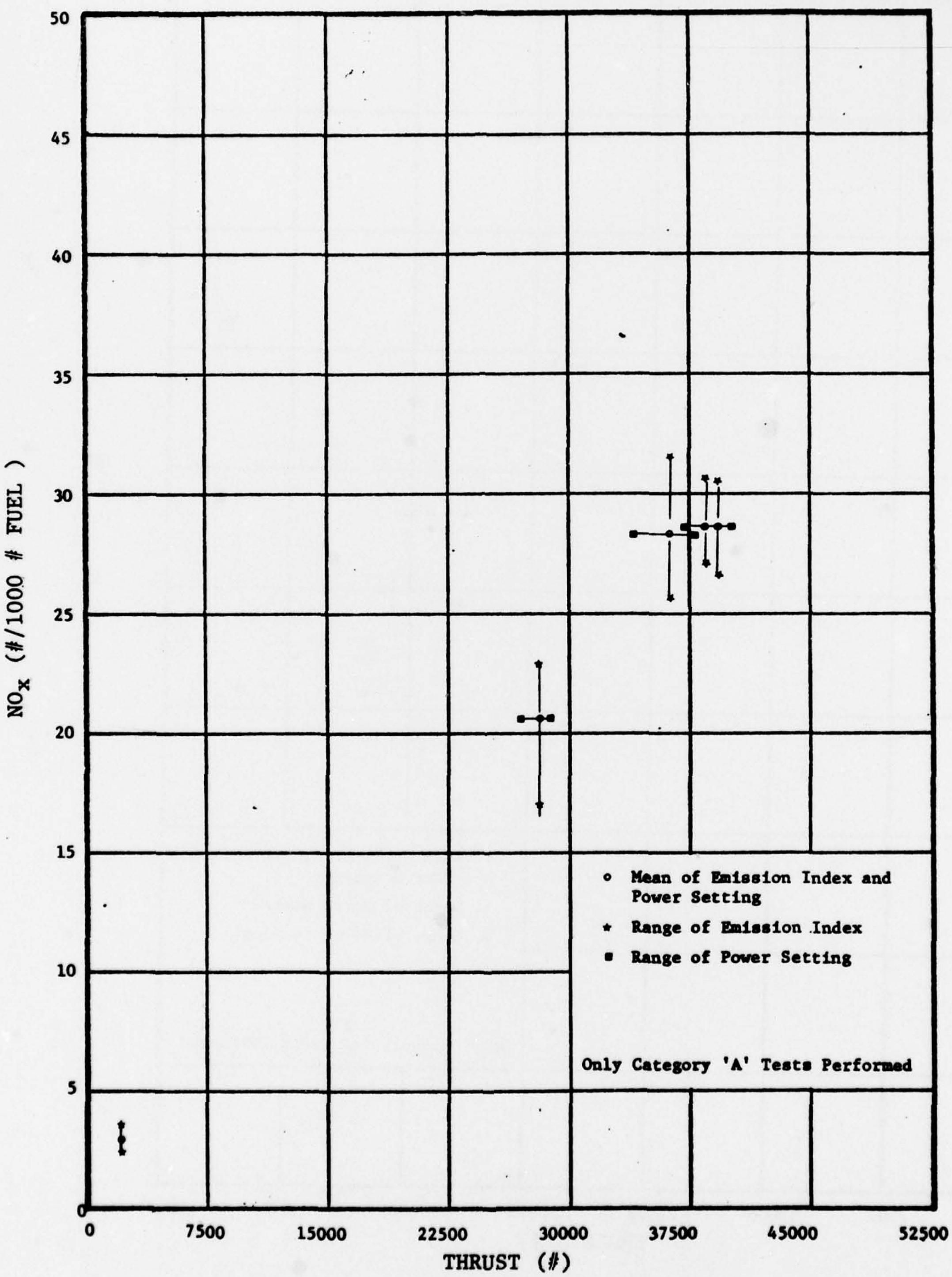


FIGURE 4-21 NO_x EMISSION INDEX VS POWER SETTING. TF39 ENGINE.

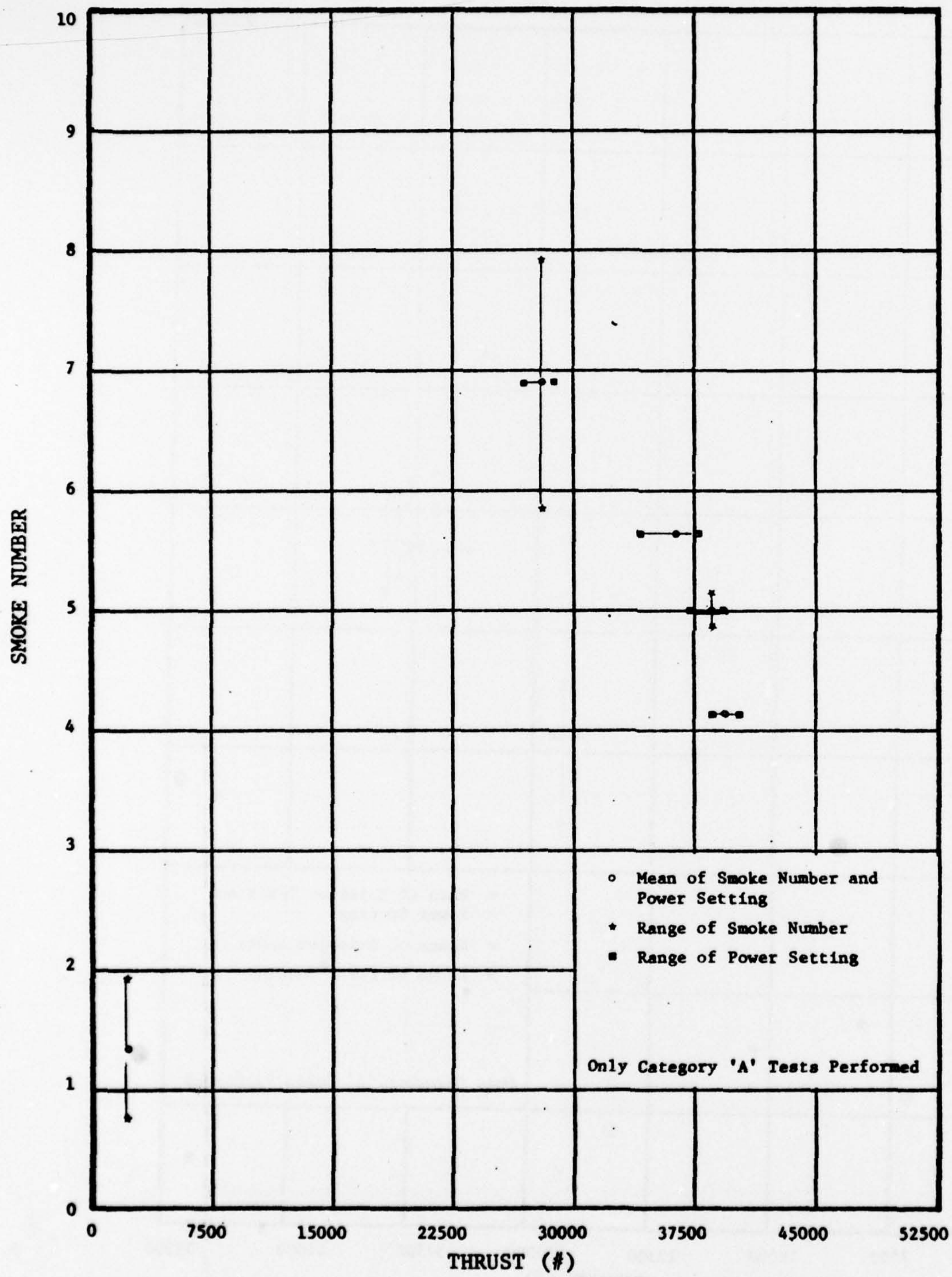


FIGURE 4-22 SMOKE NUMBER VS POWER SETTING. TF39 ENGINE.

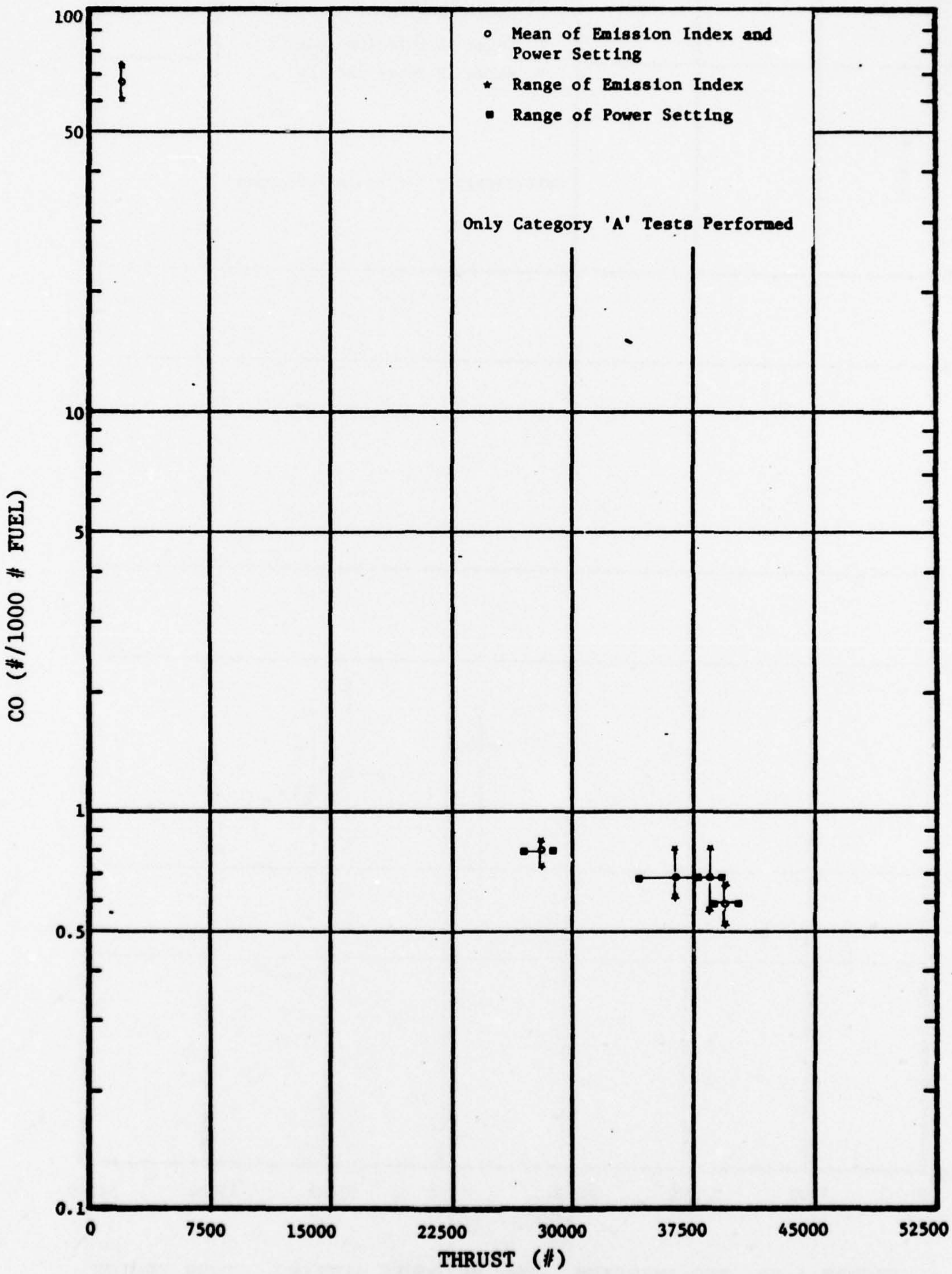


FIGURE 4-23 CO EMISSION INDEX VS POWER SETTING. TF39 ENGINE.

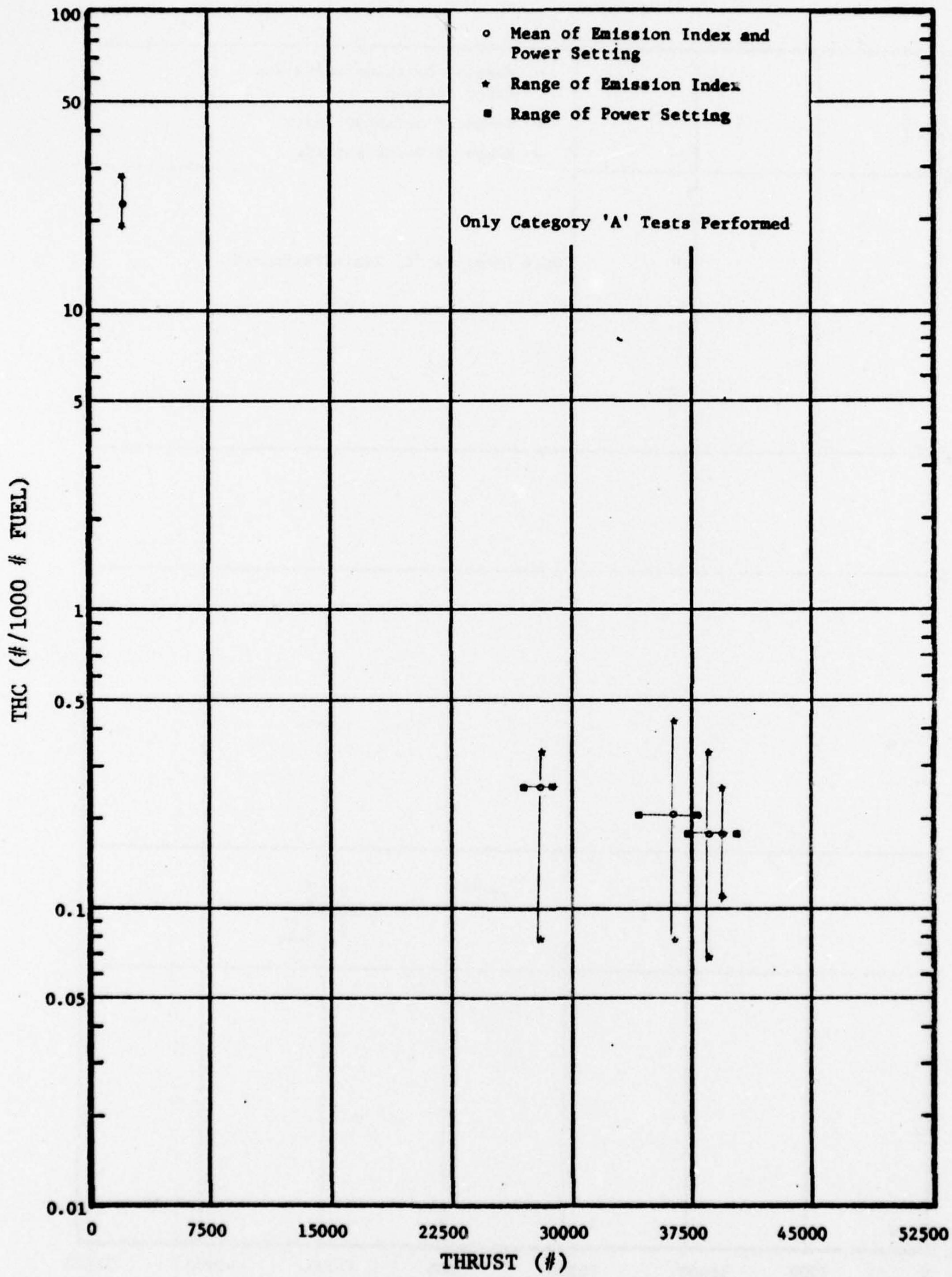


FIGURE 4-24 THC EMISSION INDEX VS POWER SETTING. TF39 ENGINE.

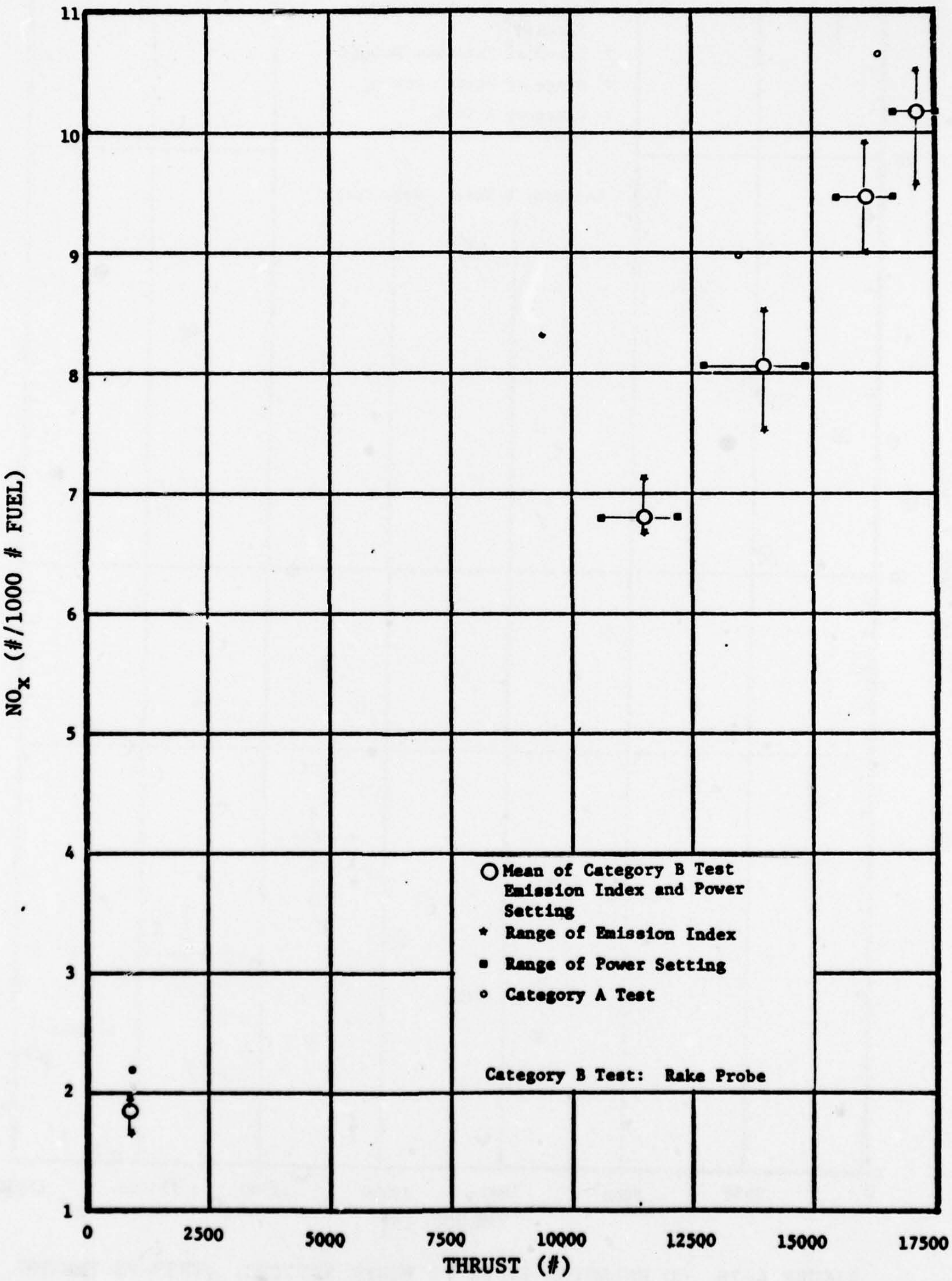


FIGURE 4-25 NO_x EMISSION INDEX VS POWER SETTING. TF33-P3 ENGINE

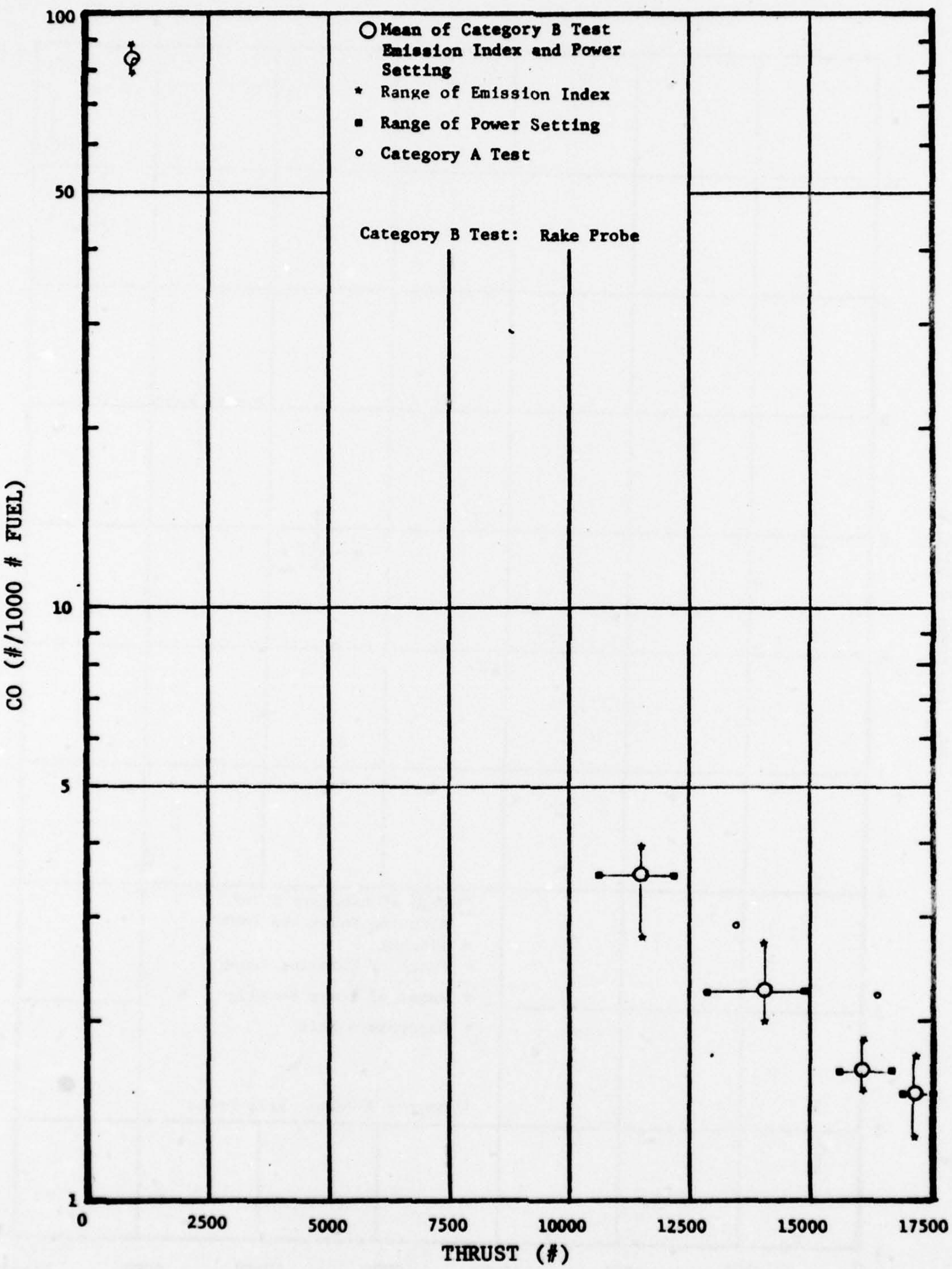


FIGURE 4-26 CO EMISSION INDEX VS POWER SETTING. TF33-P3 ENGINE.

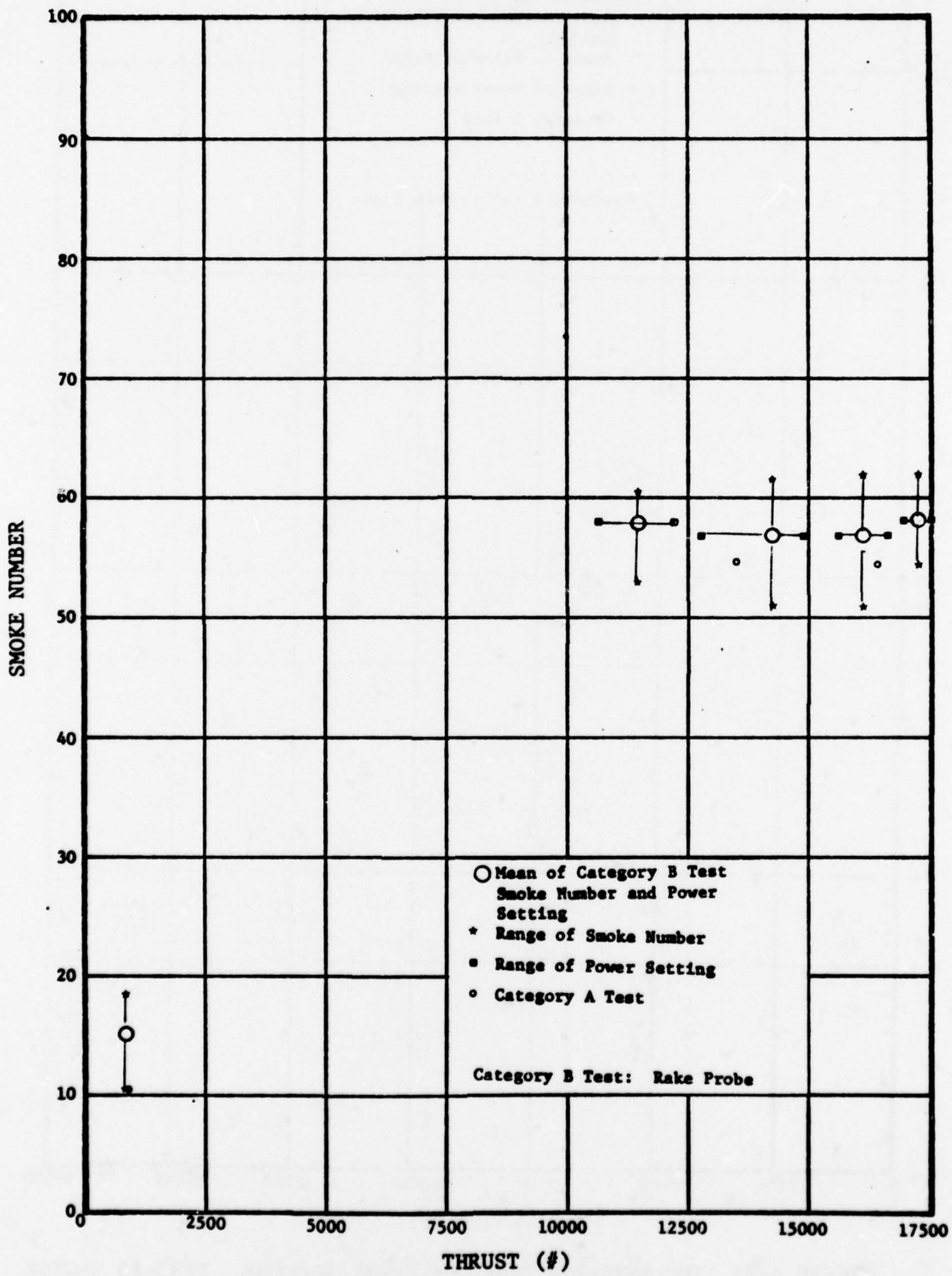


FIGURE 4-27 SMOKE NUMBER VS POWER SETTING. TF33-P3 ENGINE.

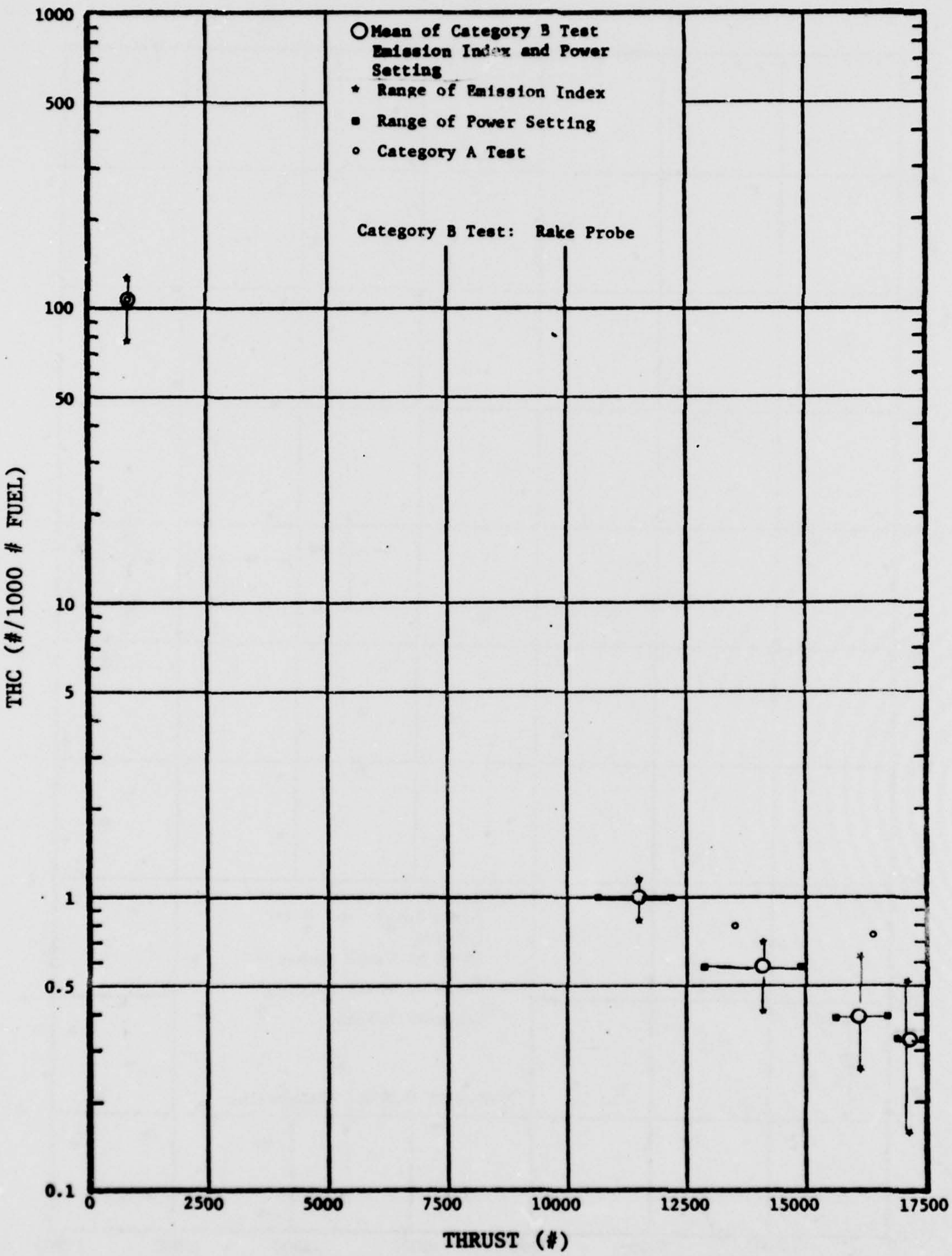


FIGURE 4-28 THC EMISSION INDEX VS POWER SETTING. TF33-P3 ENGINE.

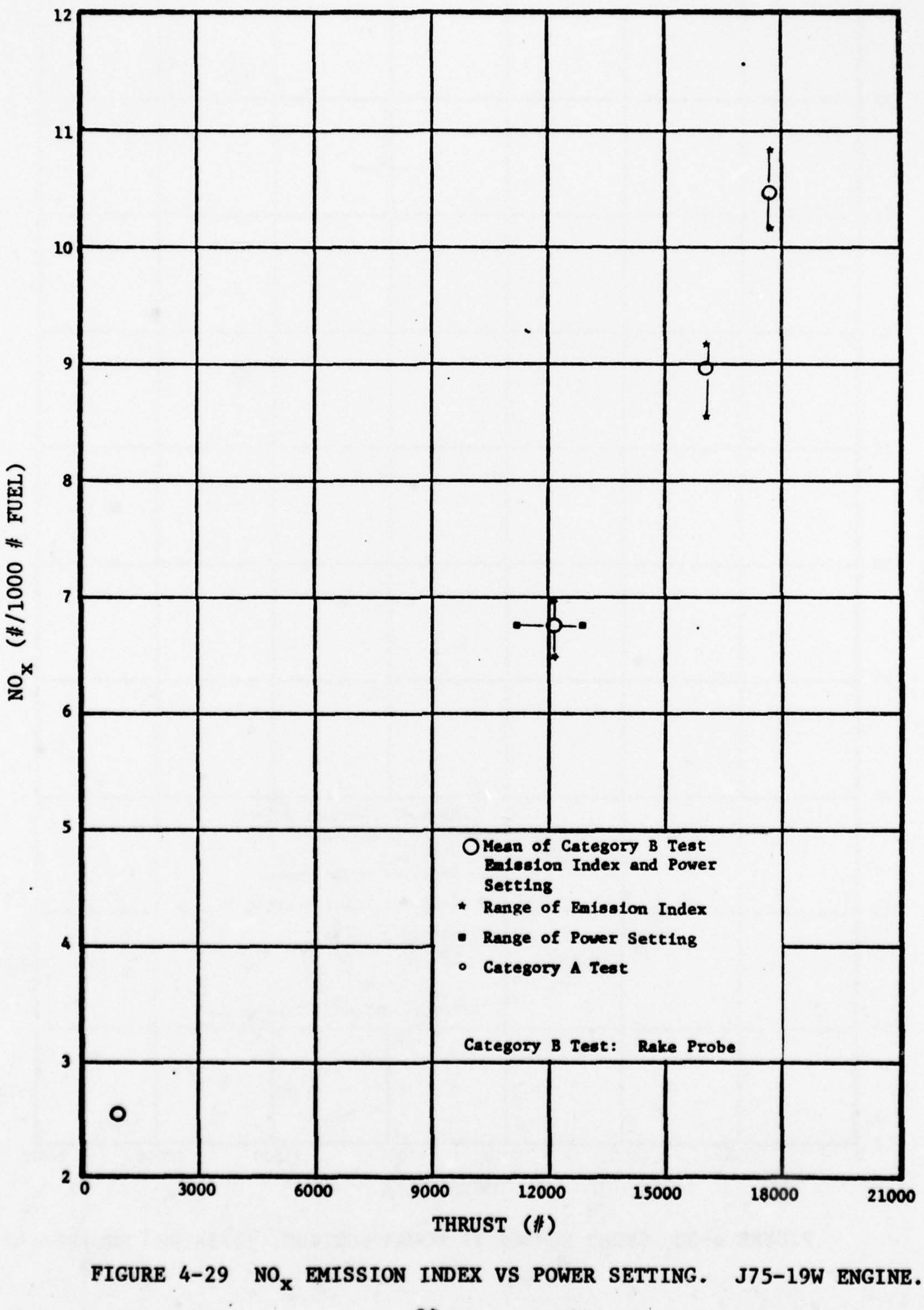


FIGURE 4-29 NO_x EMISSION INDEX VS POWER SETTING. J75-19W ENGINE.

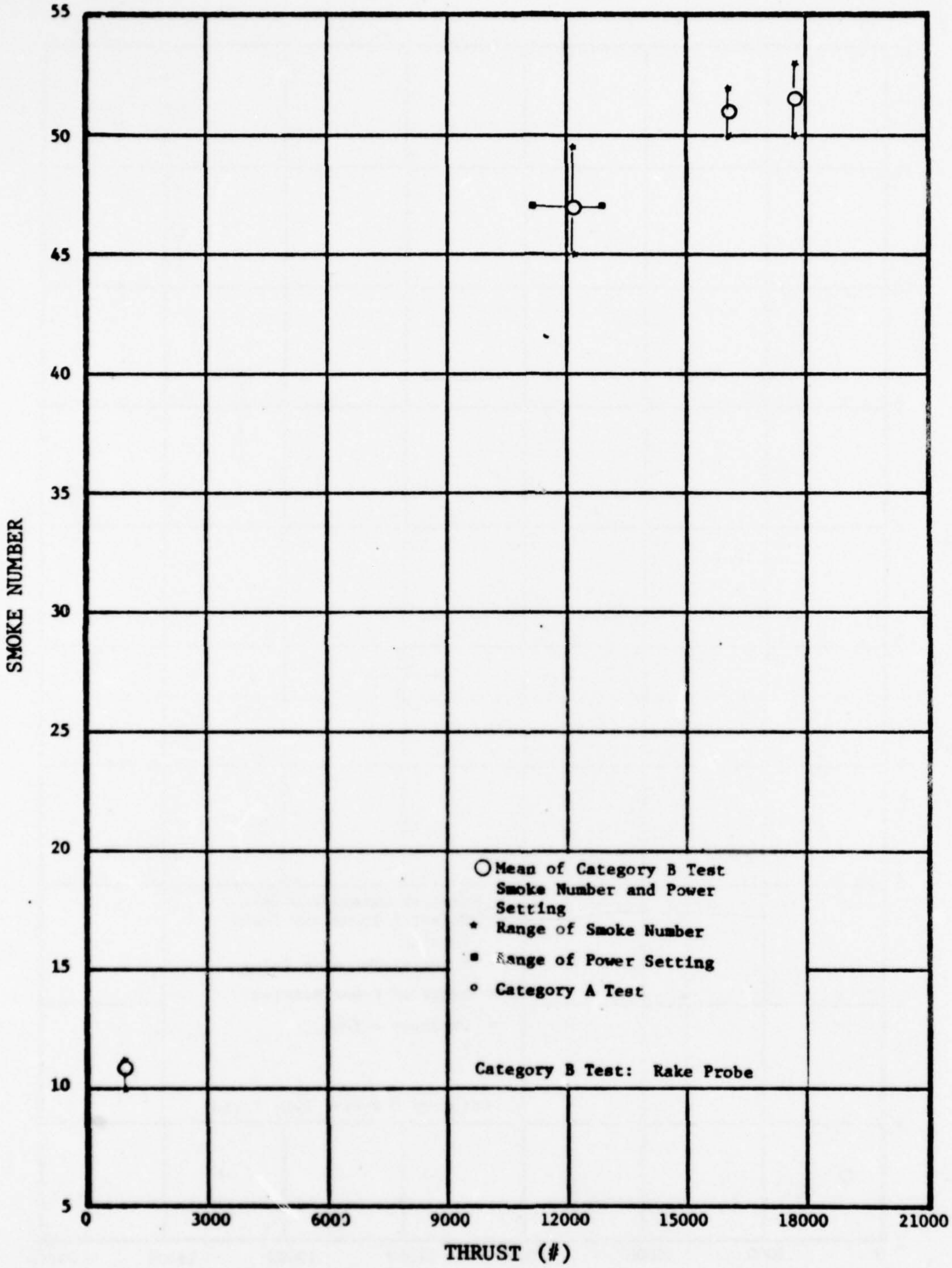


FIGURE 4-30 SMOKE NUMBER VS POWER SETTING. J75-19W ENGINE.

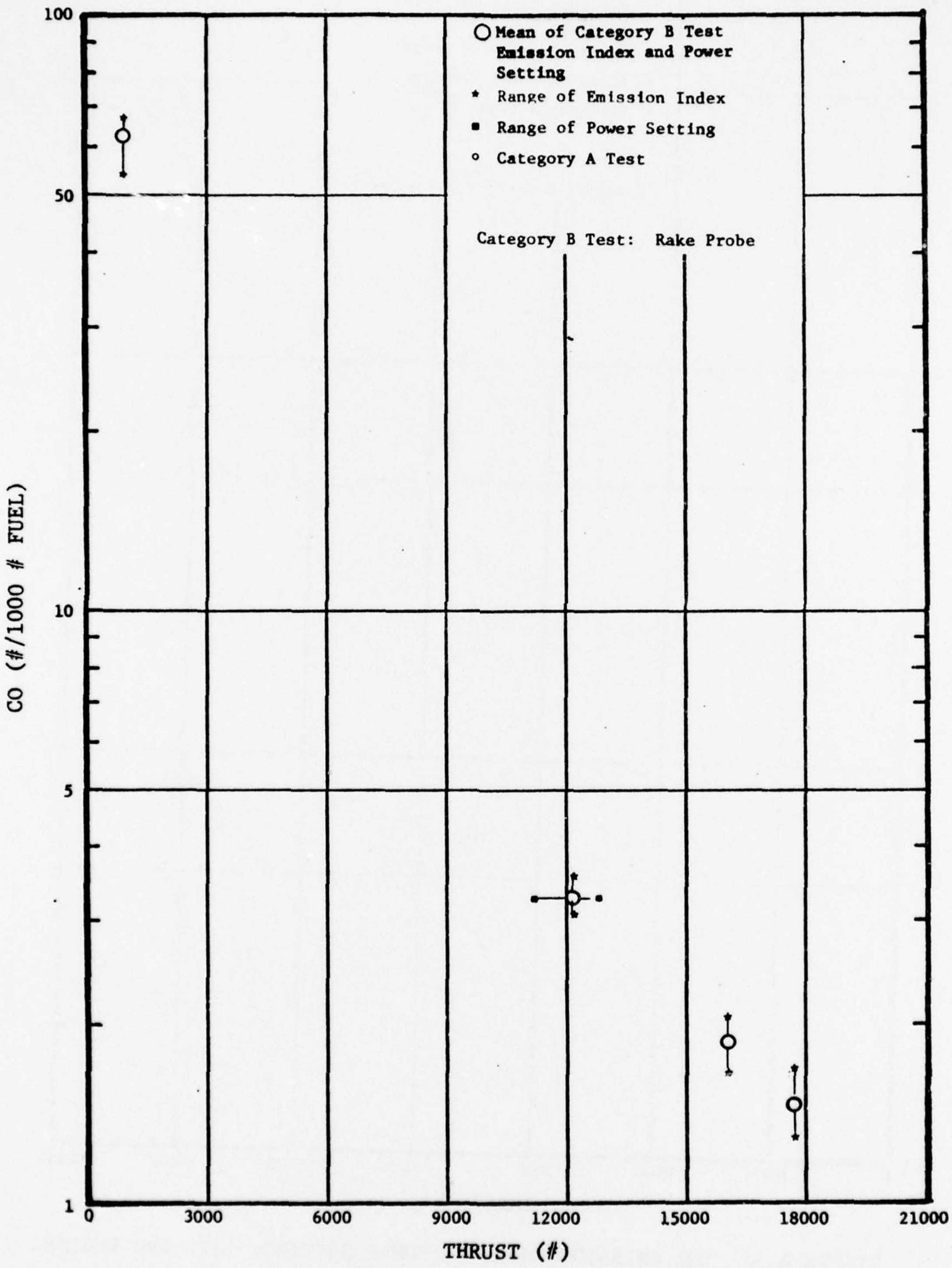


FIGURE 4-31 CO EMISSION INDEX VS POWER SETTING. J75-19W ENGINE.

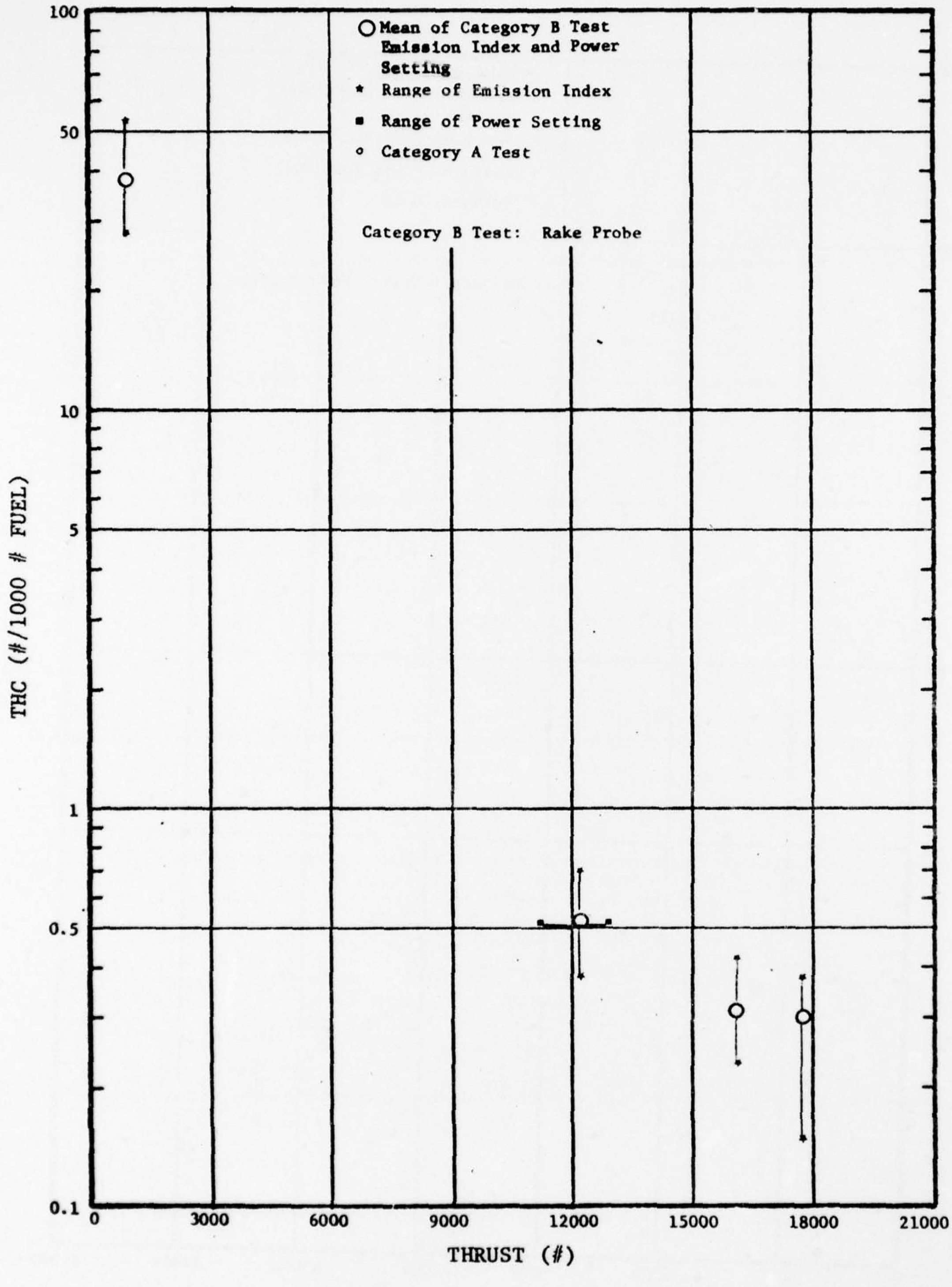


FIGURE 4-32 THC EMISSION INDEX VS POWER SETTING. J75-19W ENGINE.

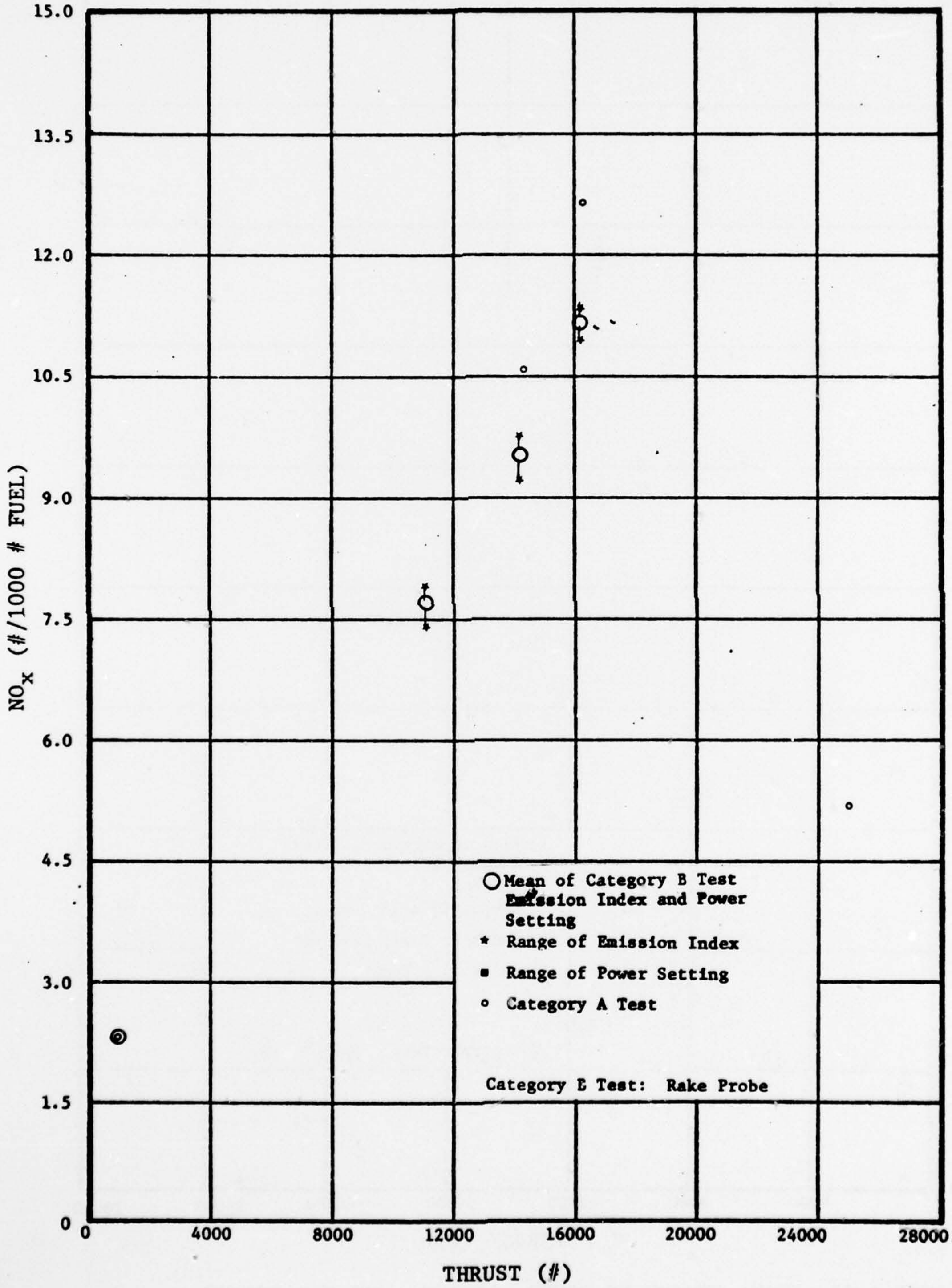


FIGURE 4-33 NO_x EMISSION INDEX VS POWER SETTING. J75-P17 ENGINE.

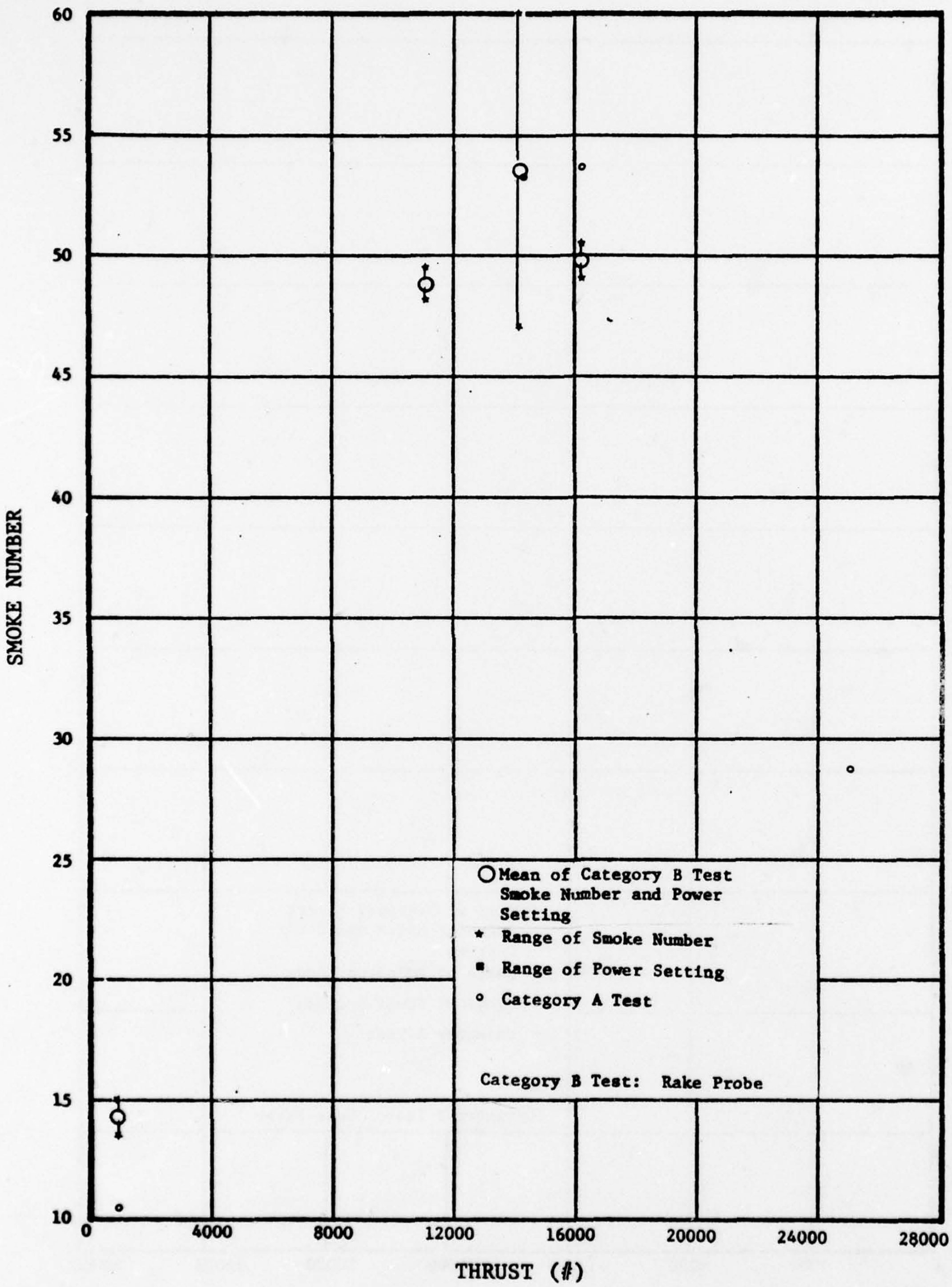


FIGURE 4-34 SMOKE NUMBER VS POWER SETTING. J75-P17 ENGINE.

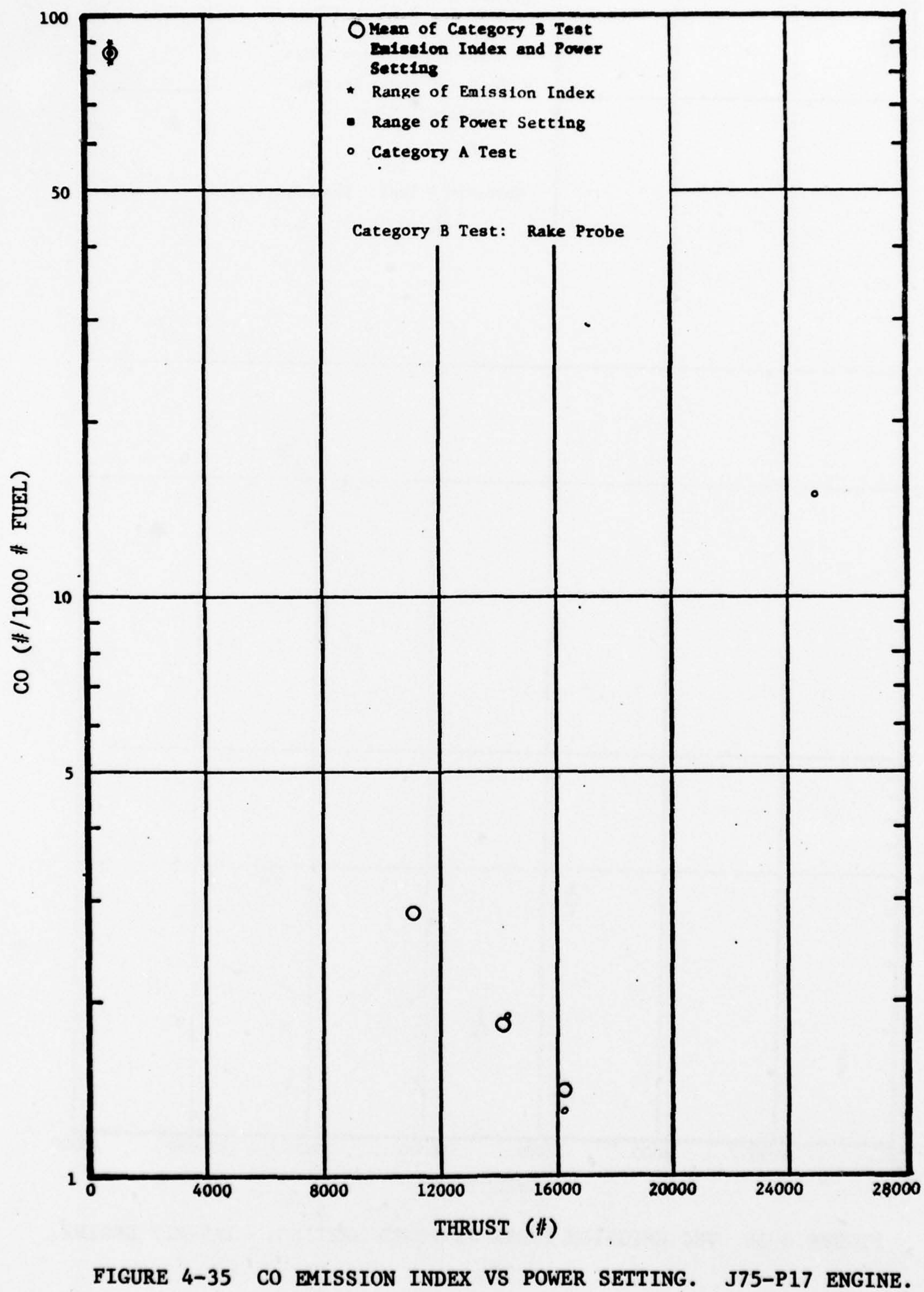


FIGURE 4-35 CO EMISSION INDEX VS POWER SETTING. J75-P17 ENGINE.

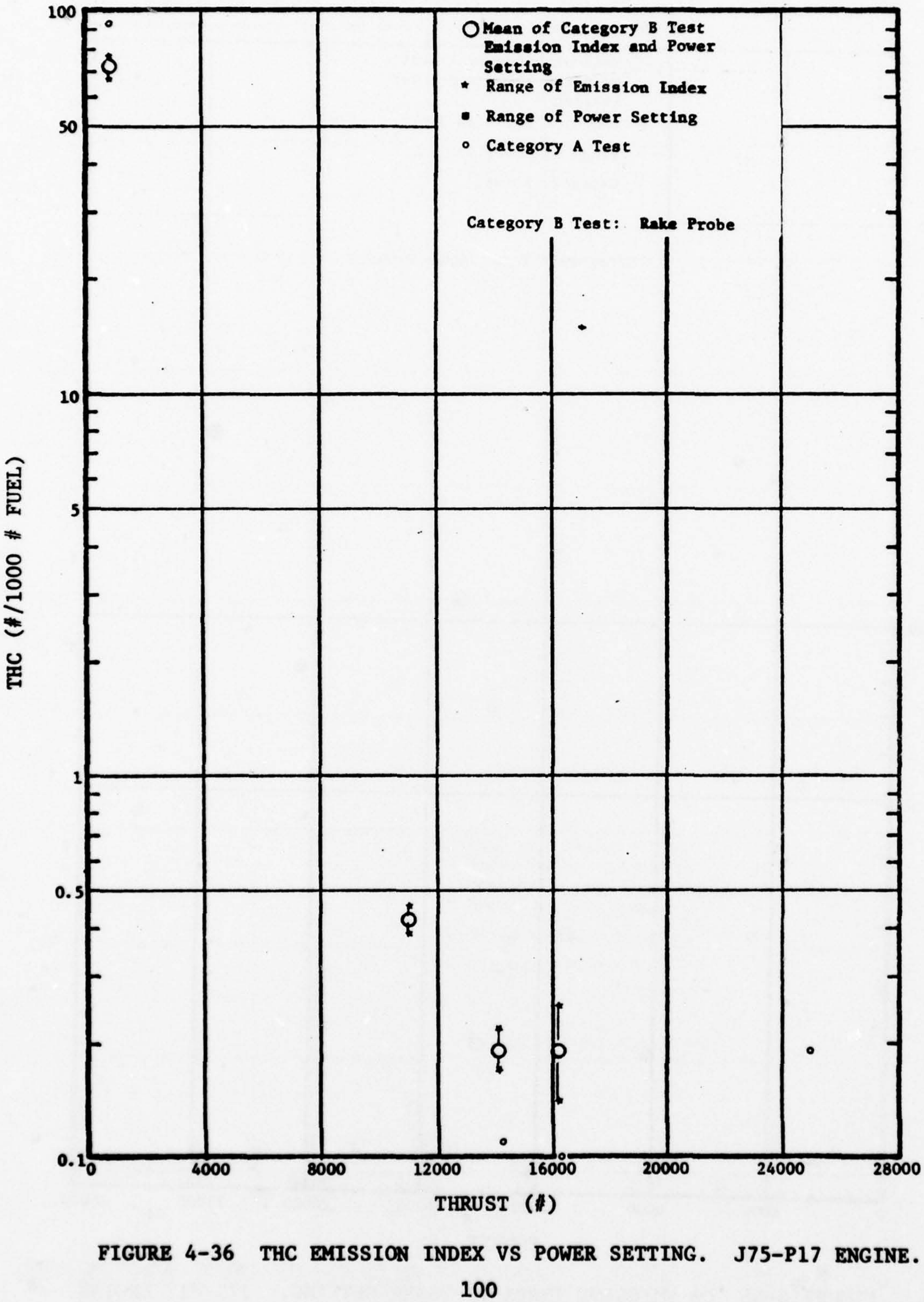


FIGURE 4-36 THC EMISSION INDEX VS POWER SETTING. J75-P17 ENGINE.

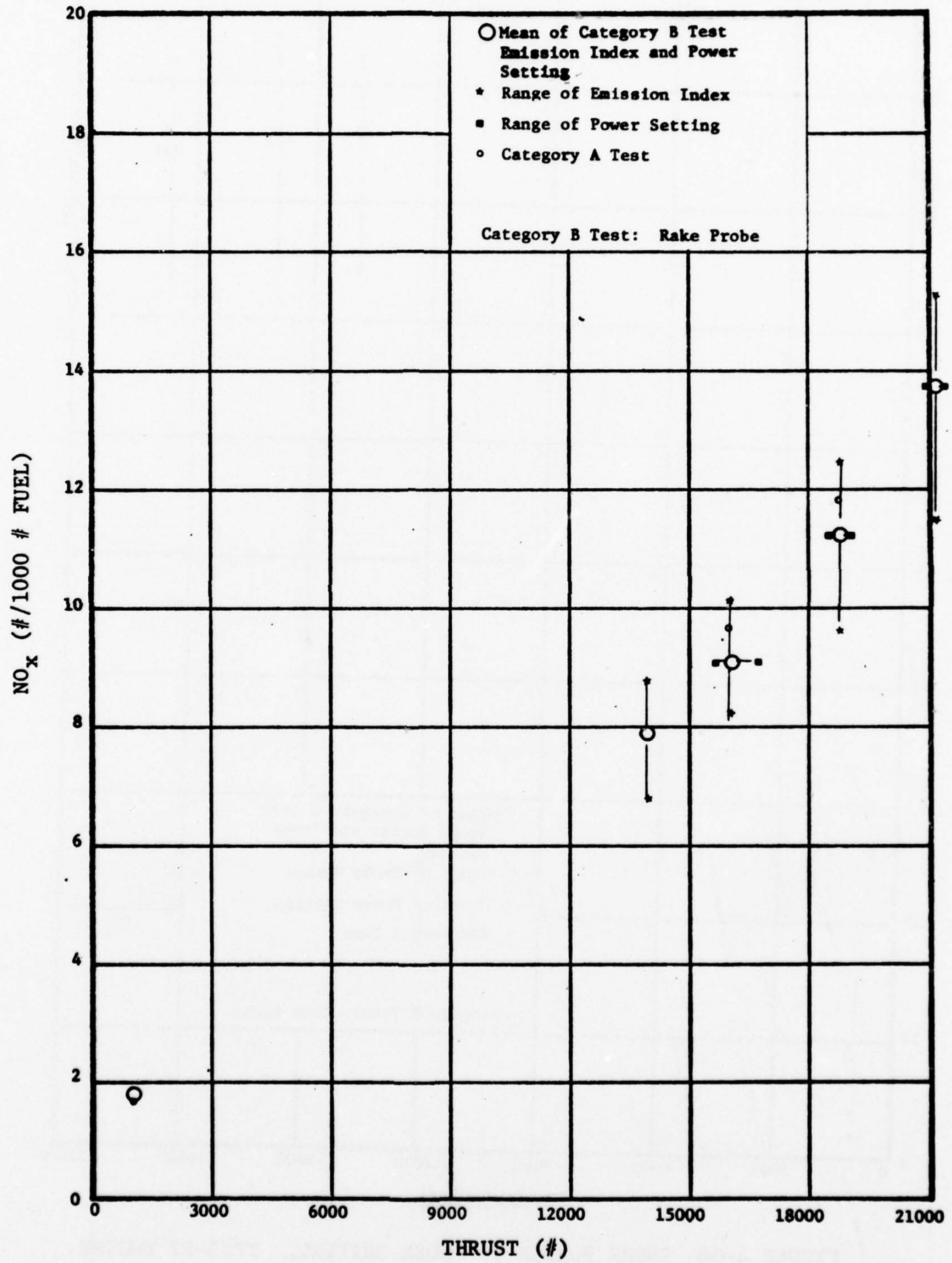


FIGURE 4-37 NO_x EMISSION INDEX VS POWER SETTING. TF33-P7 ENGINE.

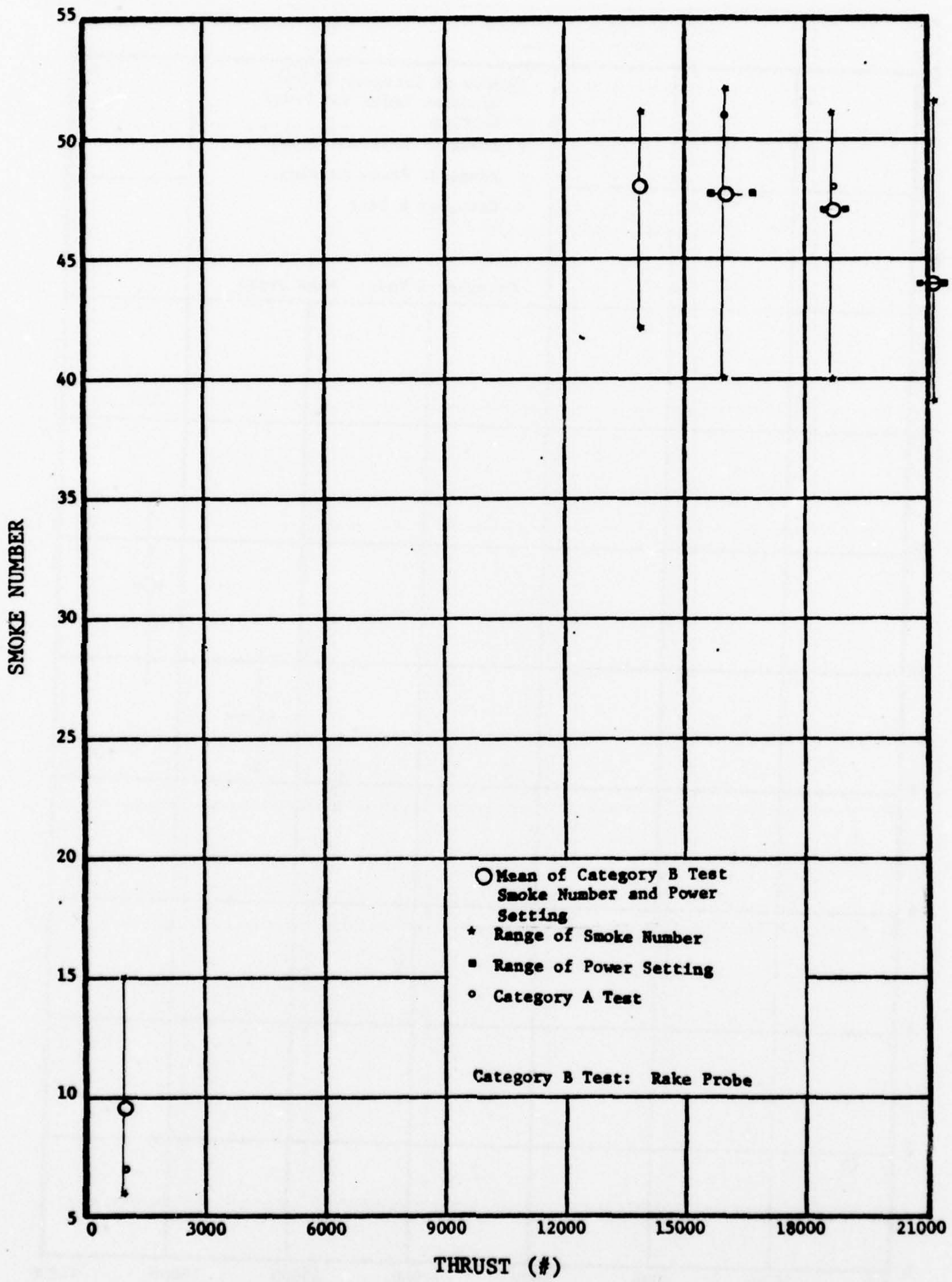


FIGURE 4-38 SMOKE NUMBER VS POWER SETTING. TF33-P7 ENGINE.

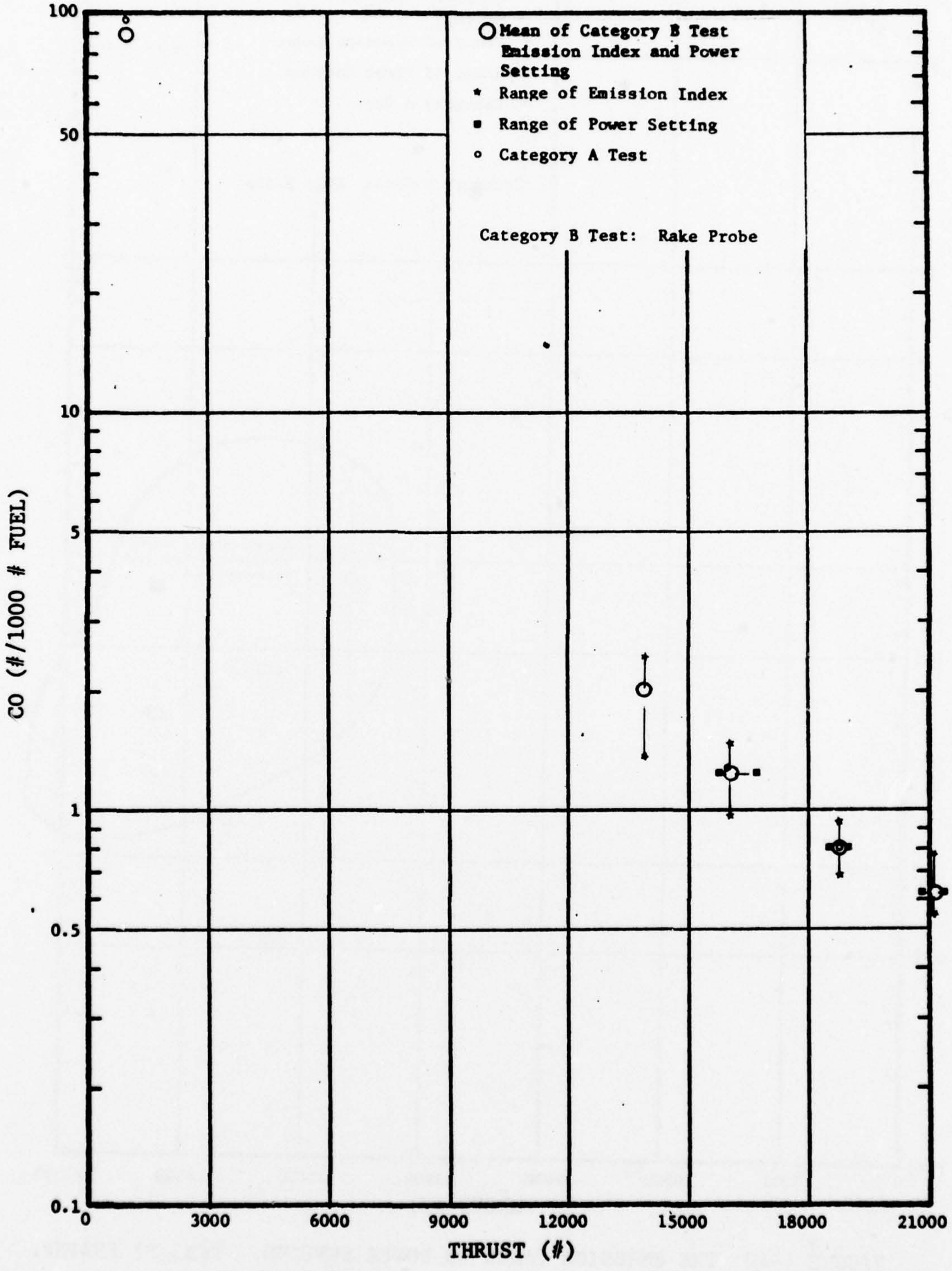


FIGURE 4-39 CO EMISSION INDEX VS POWER SETTING. TF33-P7 ENGINE.

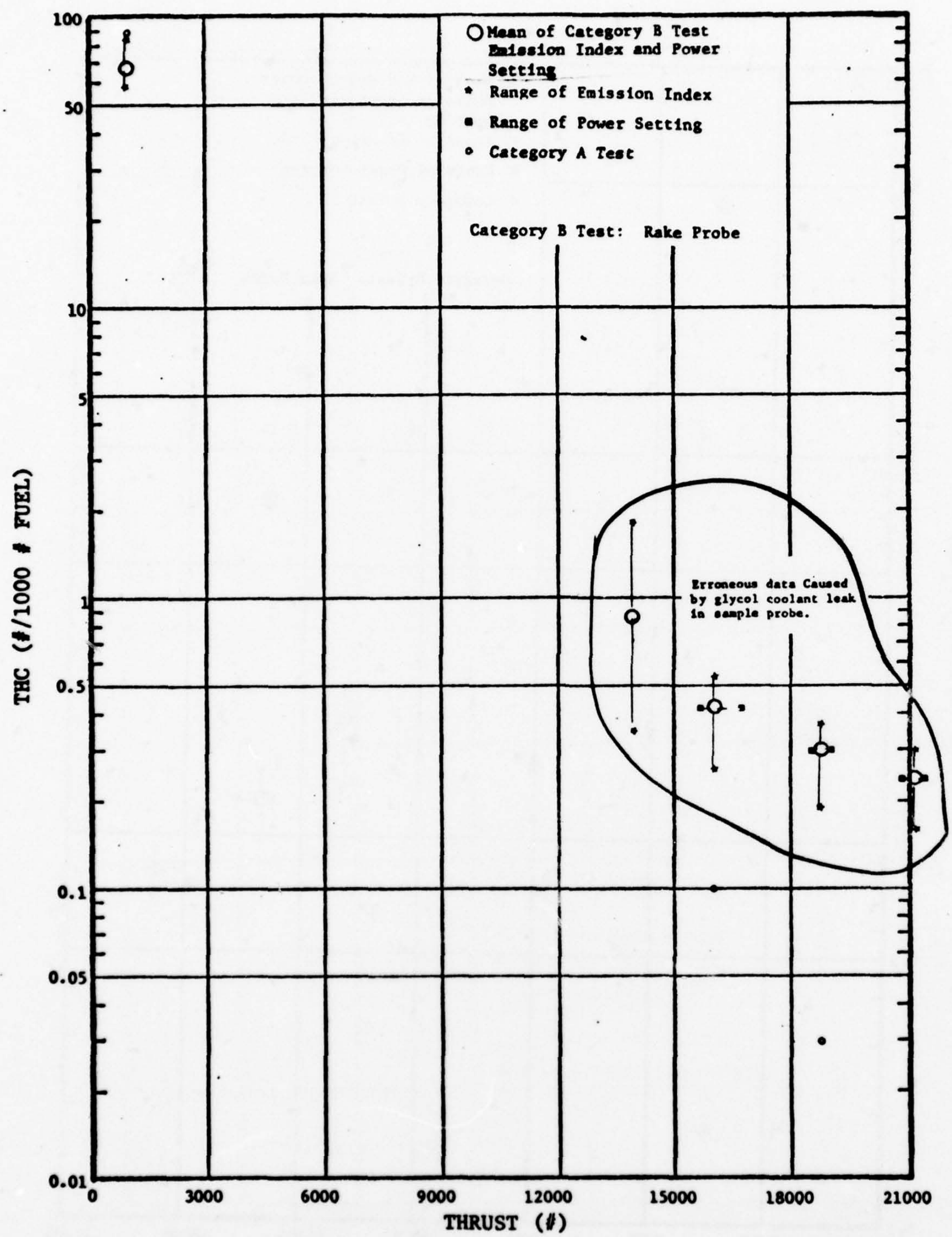


FIGURE 4-40 THC EMISSION INDEX VS POWER SETTING. TF33-P7 ENGINE.

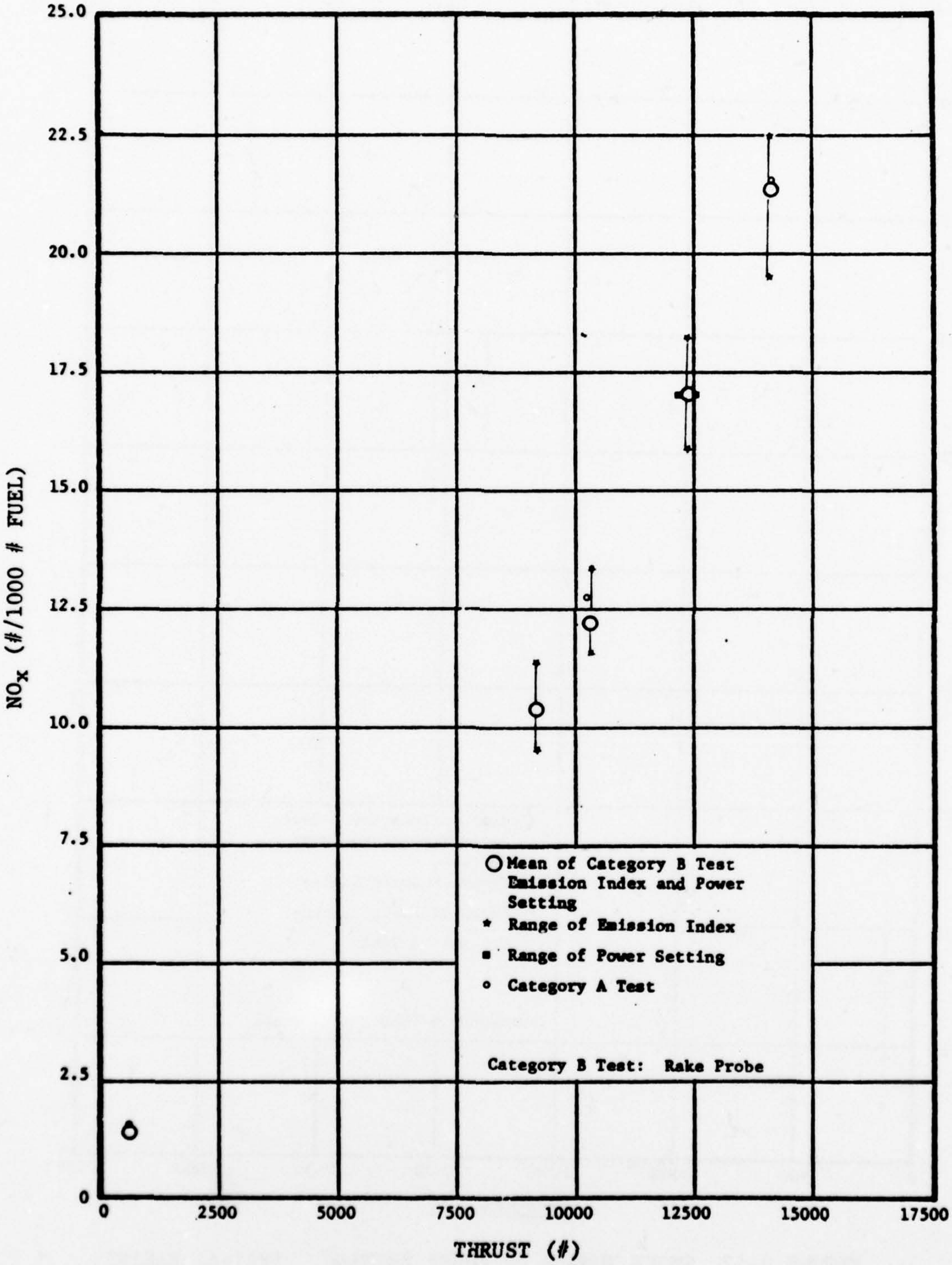


FIGURE 4-41 NO_x EMISSION INDEX VS POWER SETTING. TF41-A1 ENGINE

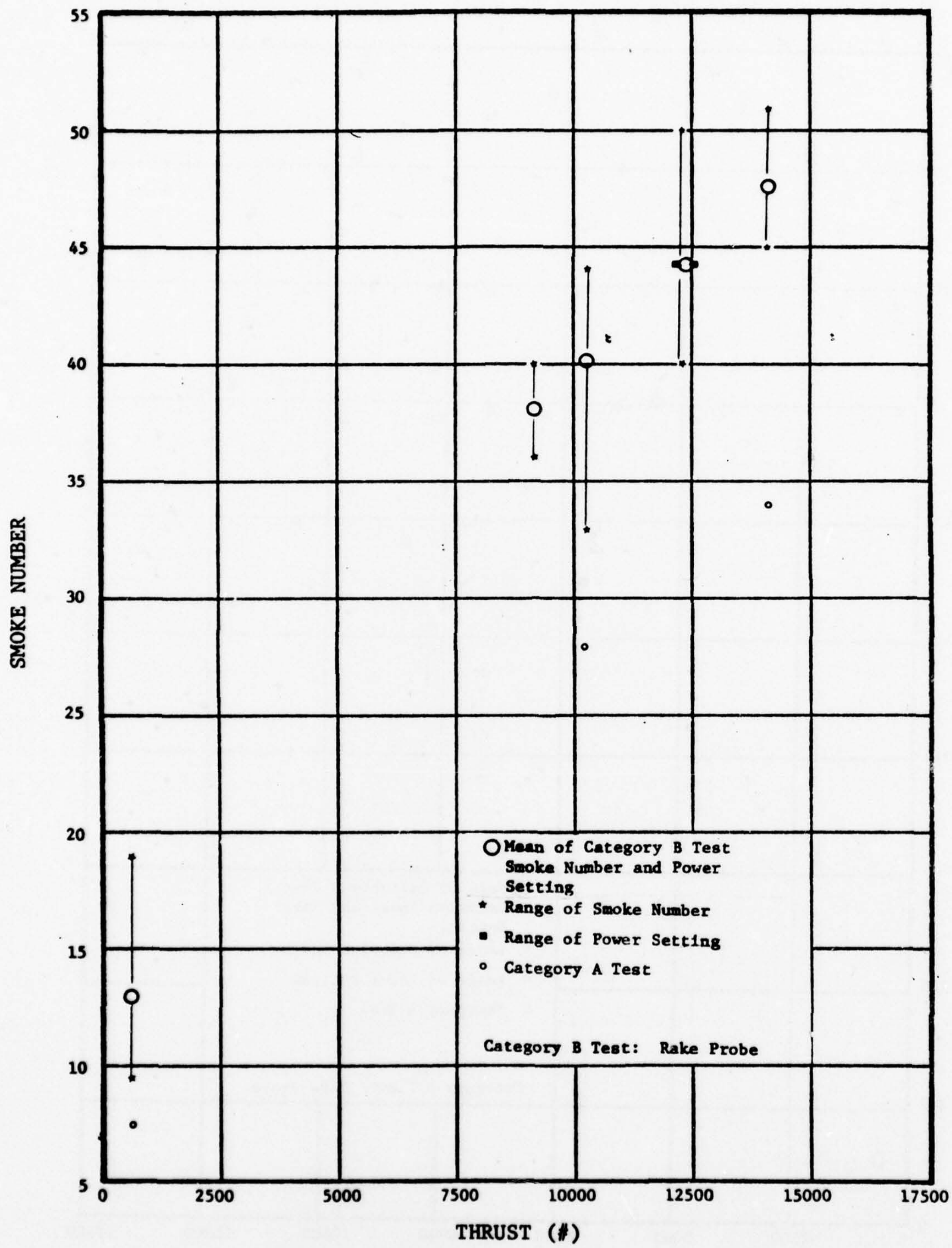


FIGURE 4-42 SMOKE NUMBER VS POWER SETTING. TF41-A1 ENGINE.

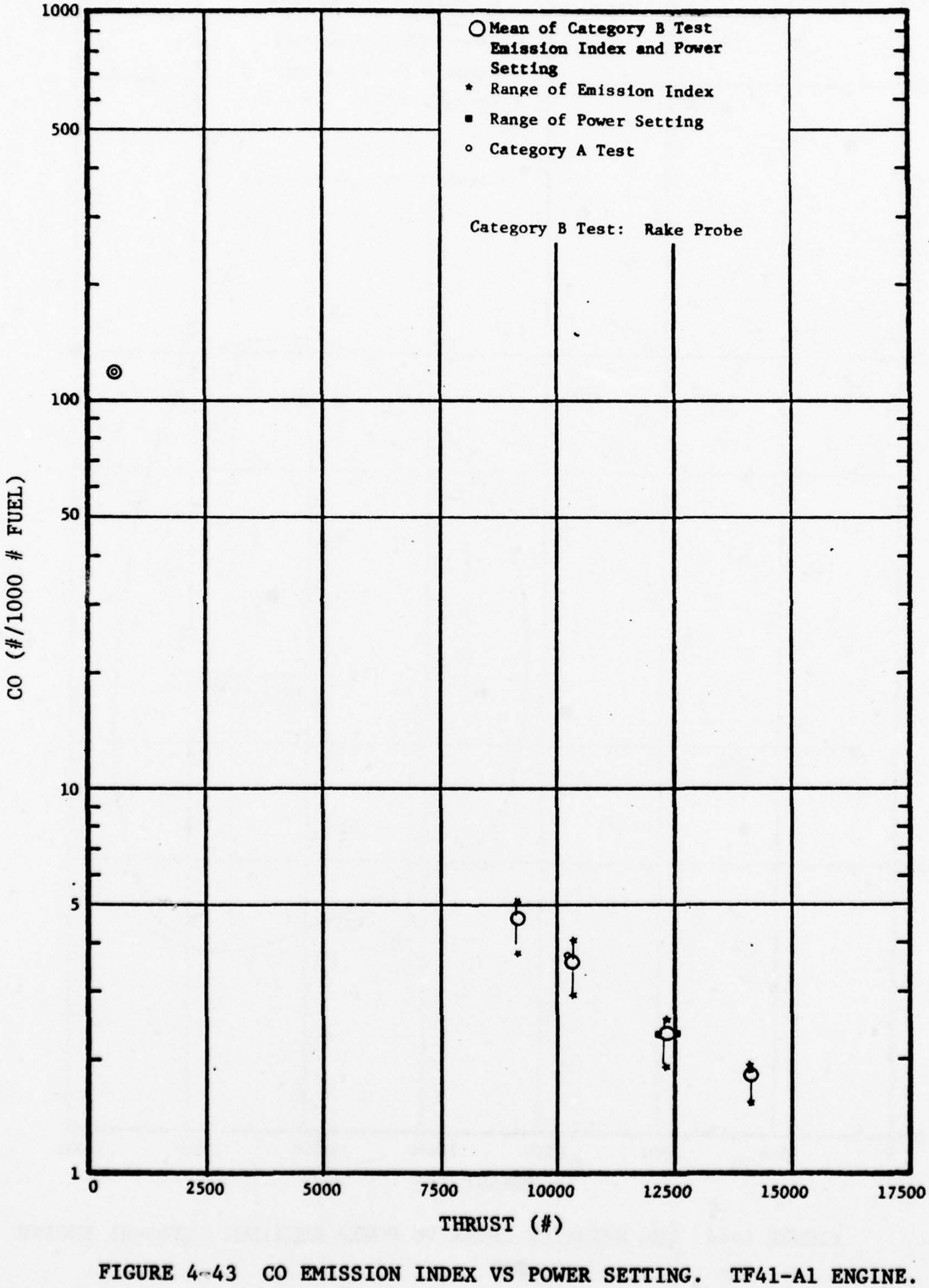


FIGURE 4-43 CO EMISSION INDEX VS POWER SETTING. TF41-A1 ENGINE.

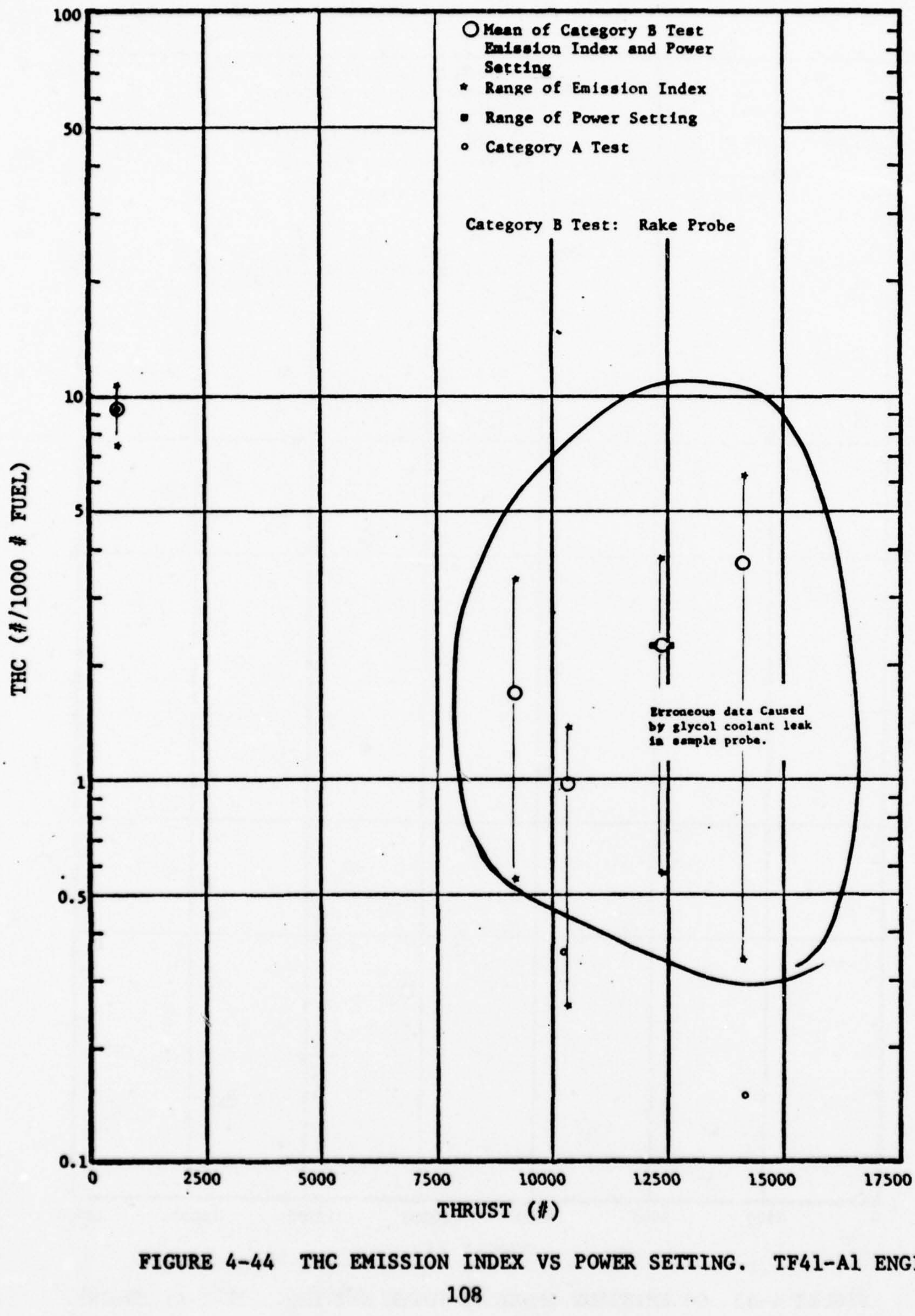


FIGURE 4-44 THC EMISSION INDEX VS POWER SETTING. TF41-A1 ENGINE

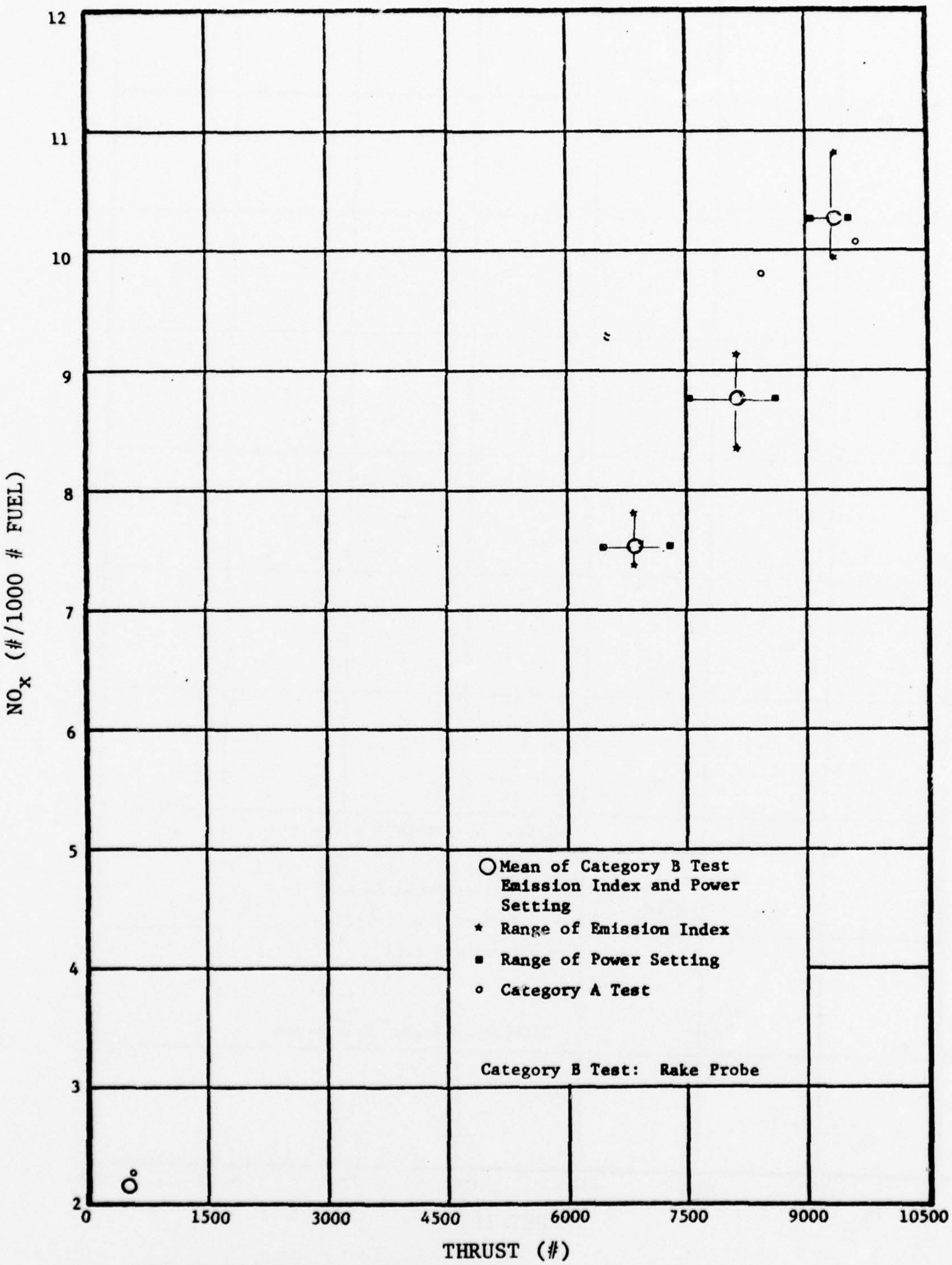


FIGURE 4-45 NO_x EMISSION INDEX VS POWER SETTING. J57-19W ENGINE.

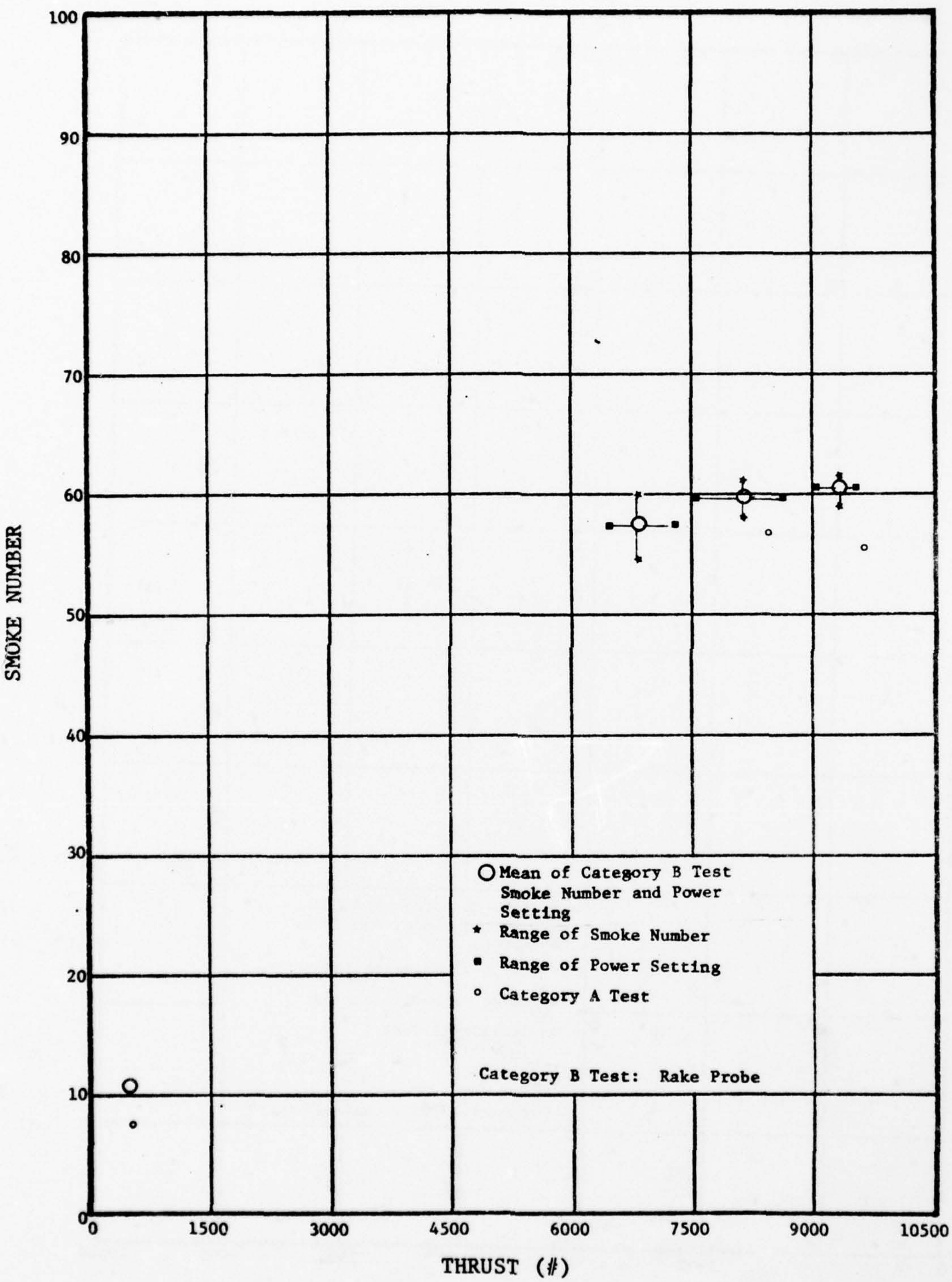


FIGURE 4-46 SMOKE NUMBER VS POWER SETTING. J57-19W ENGINE.

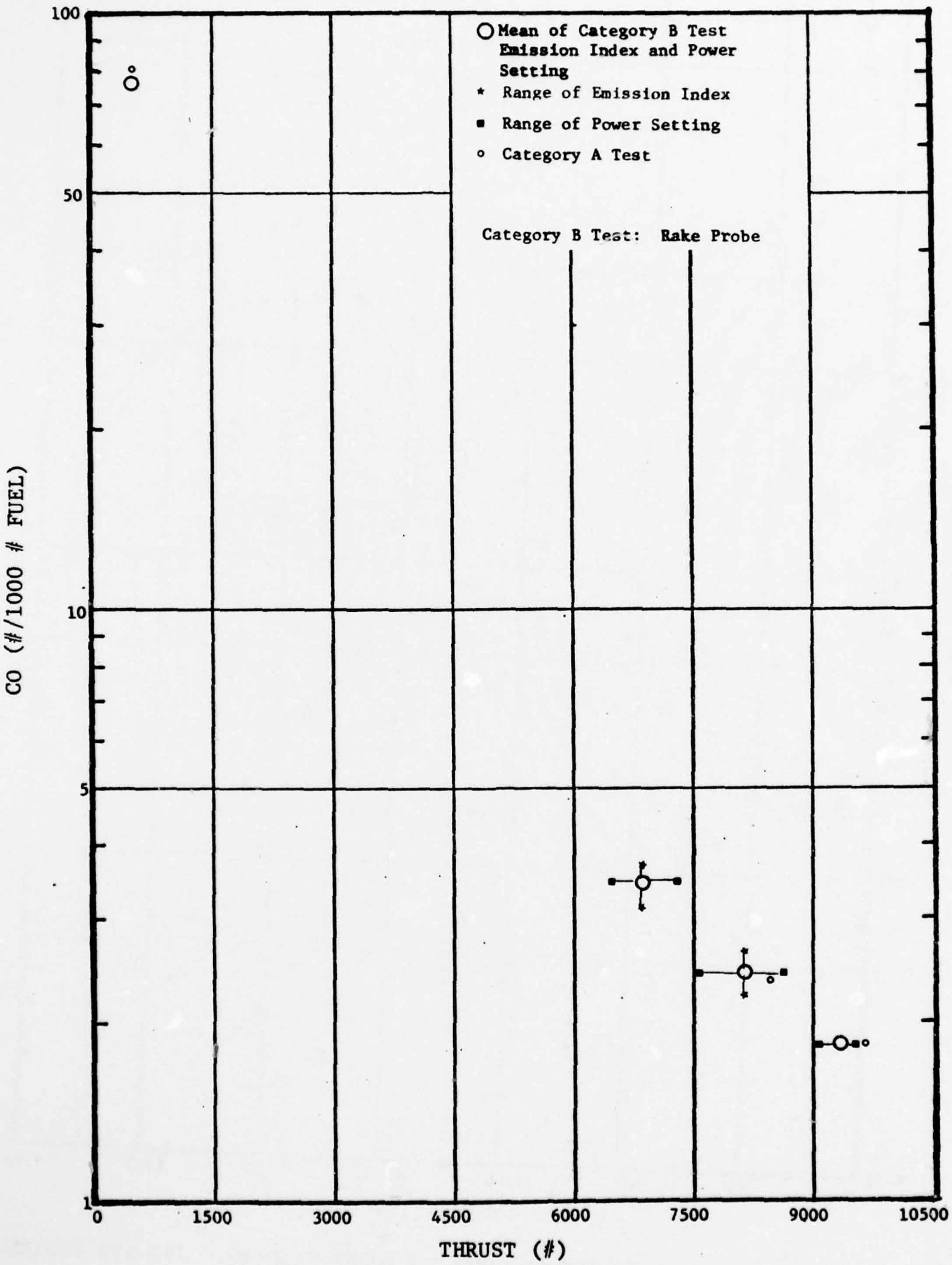


FIGURE 4-47 CO EMISSION INDEX VS POWER SETTING. J57-19W ENGINE.

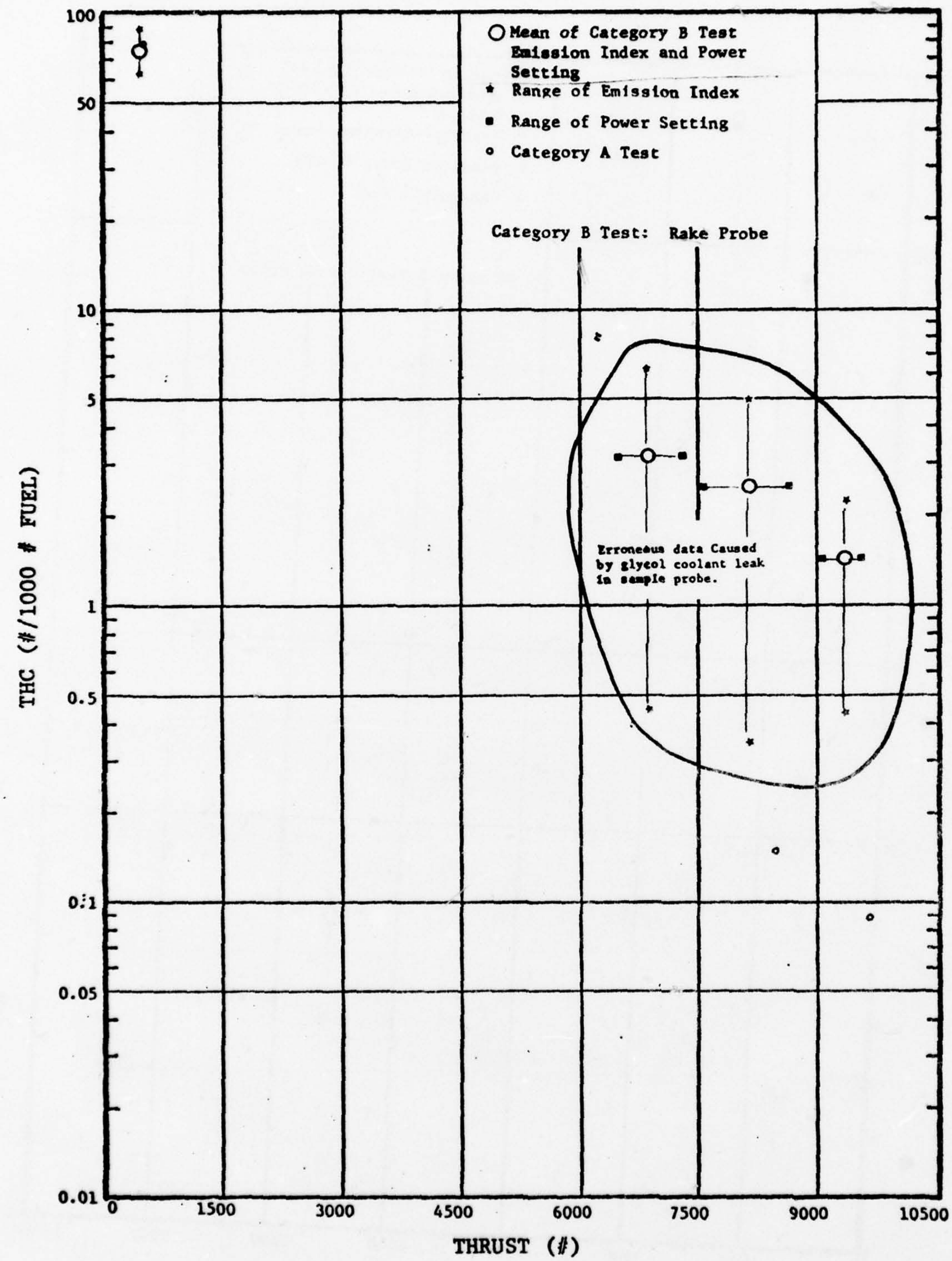


FIGURE 4-48 THC EMISSION INDEX VS POWER SETTING. J57-19W ENGINE.

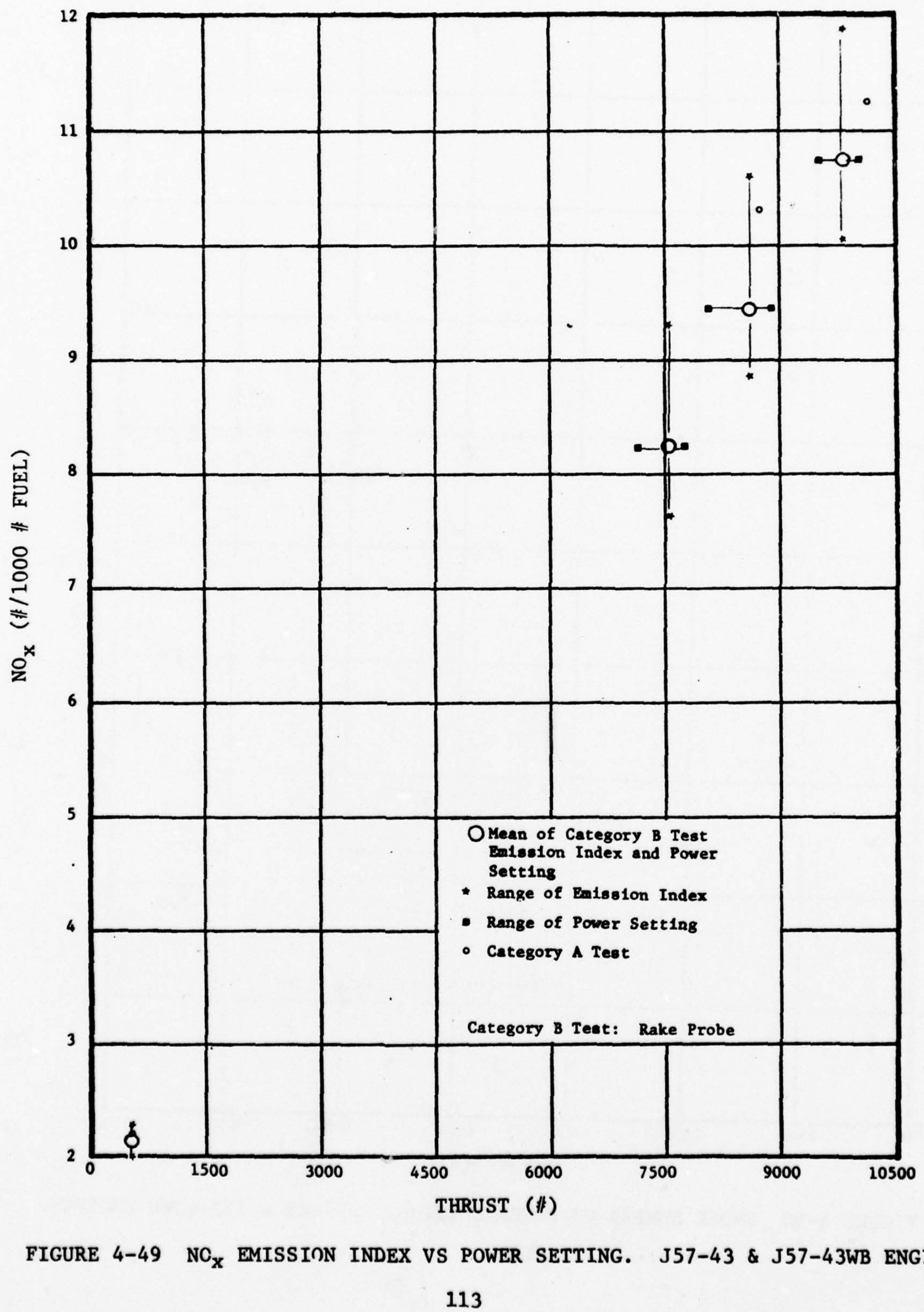


FIGURE 4-49 NO_x EMISSION INDEX VS POWER SETTING. J57-43 & J57-43WB ENGINES.

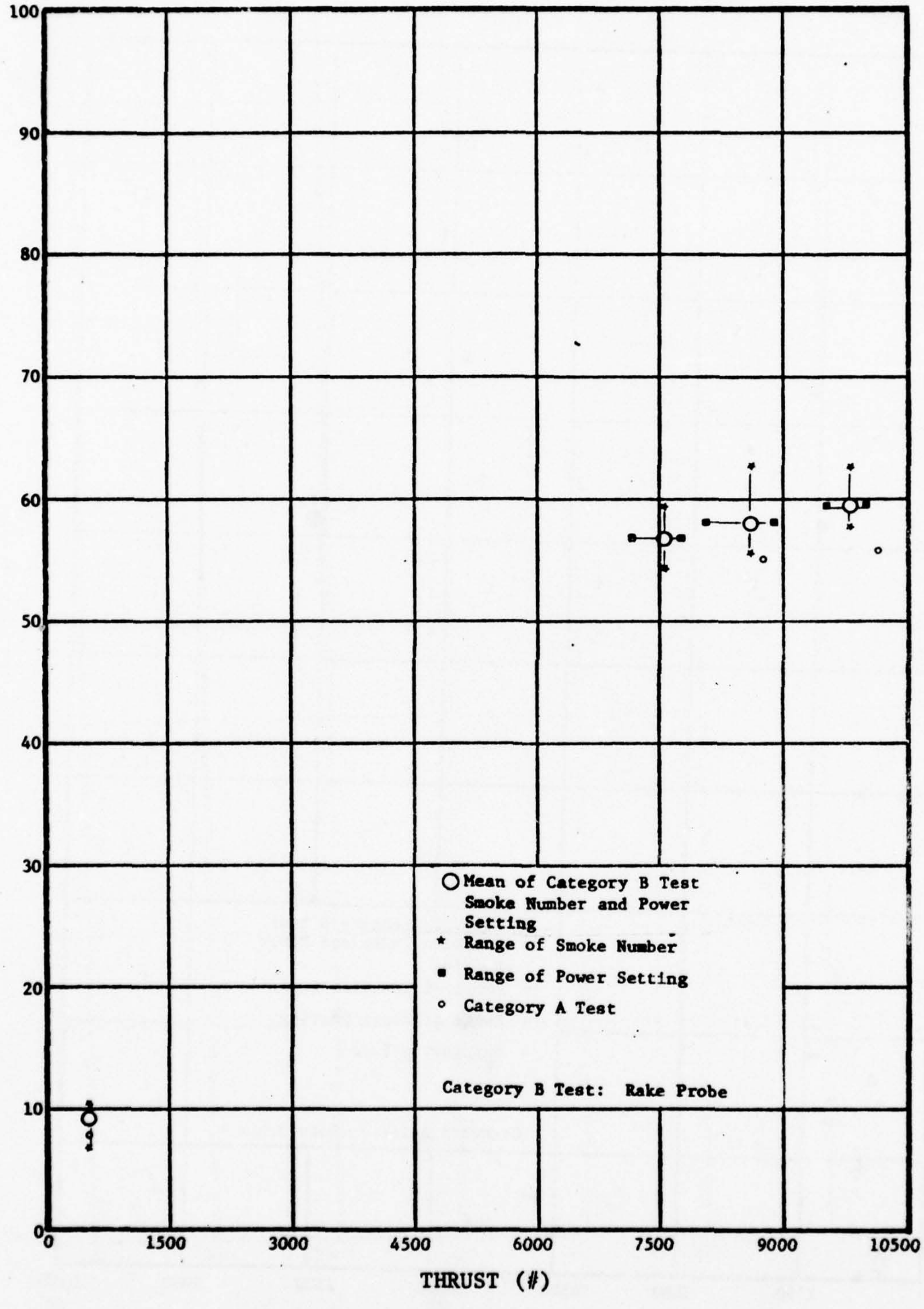


FIGURE 4-50 SMOKE NUMBER VS POWER SETTING. J57-43 & J57-43WB ENGINES.

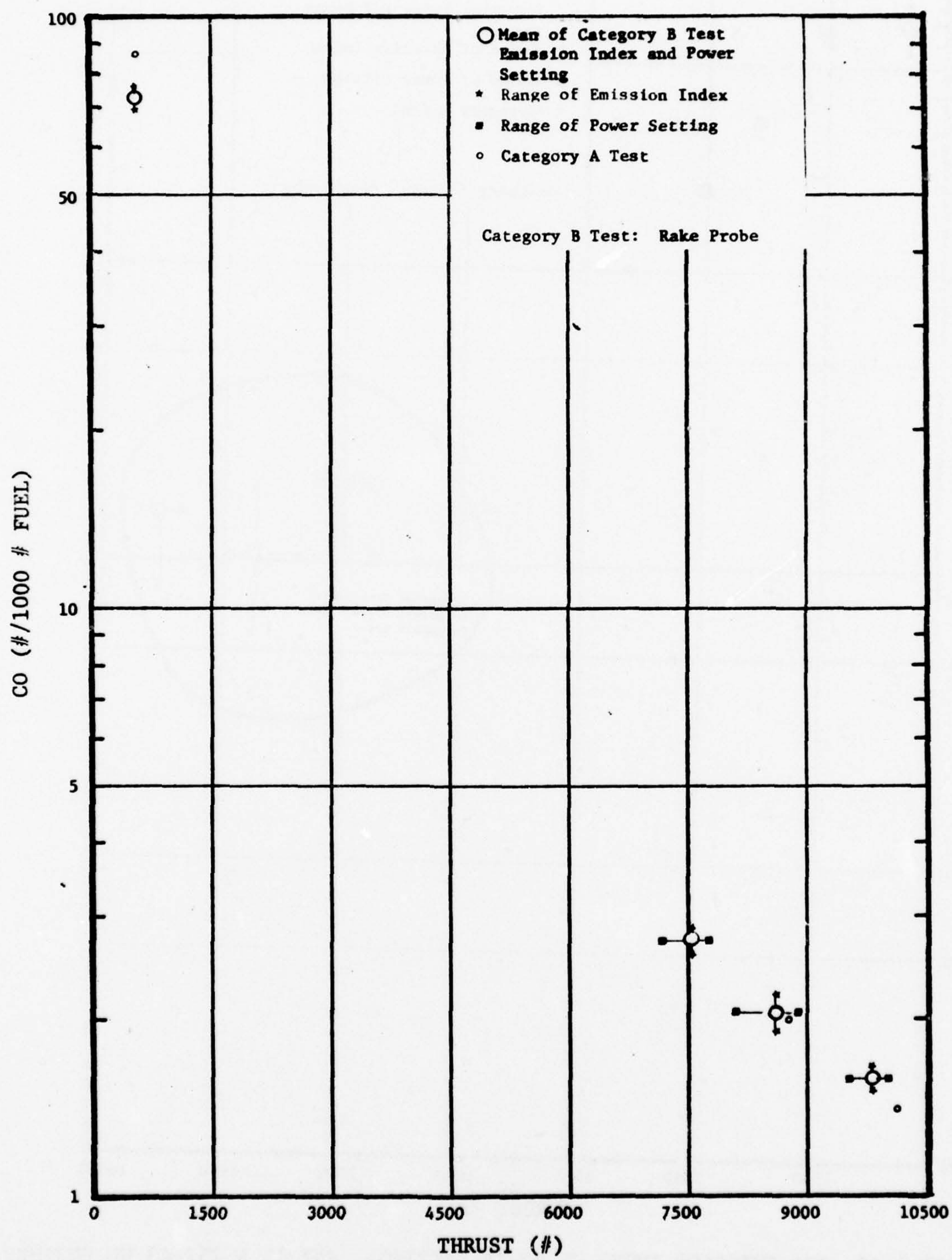


FIGURE 4-51 CO EMISSION INDEX VS POWER SETTING. J57-43 & J57-43WB ENGINES.

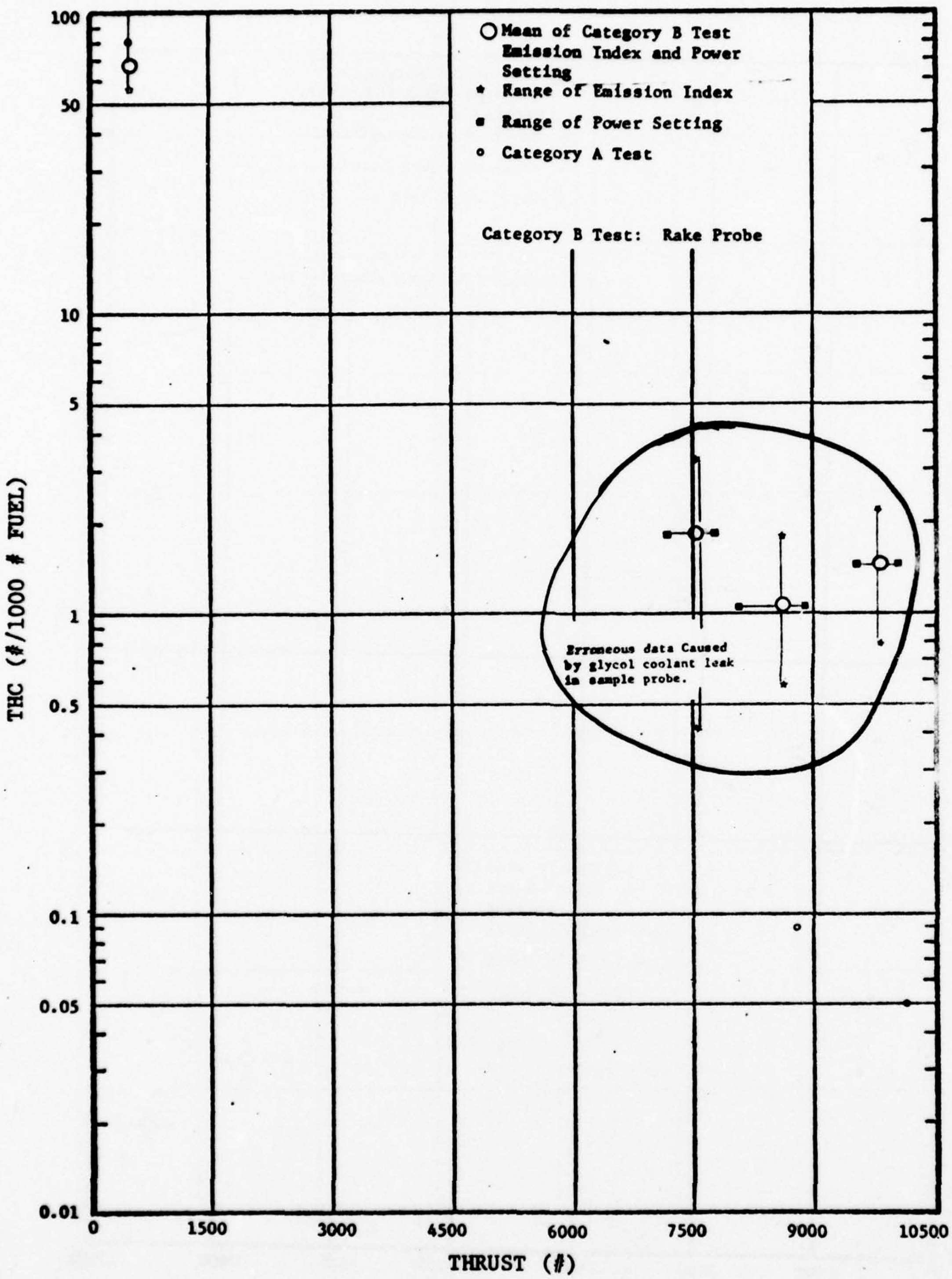


FIGURE 4-52 THC EMISSION INDEX VS POWER SETTING. J57-43 & J57-43 WB ENGINES.

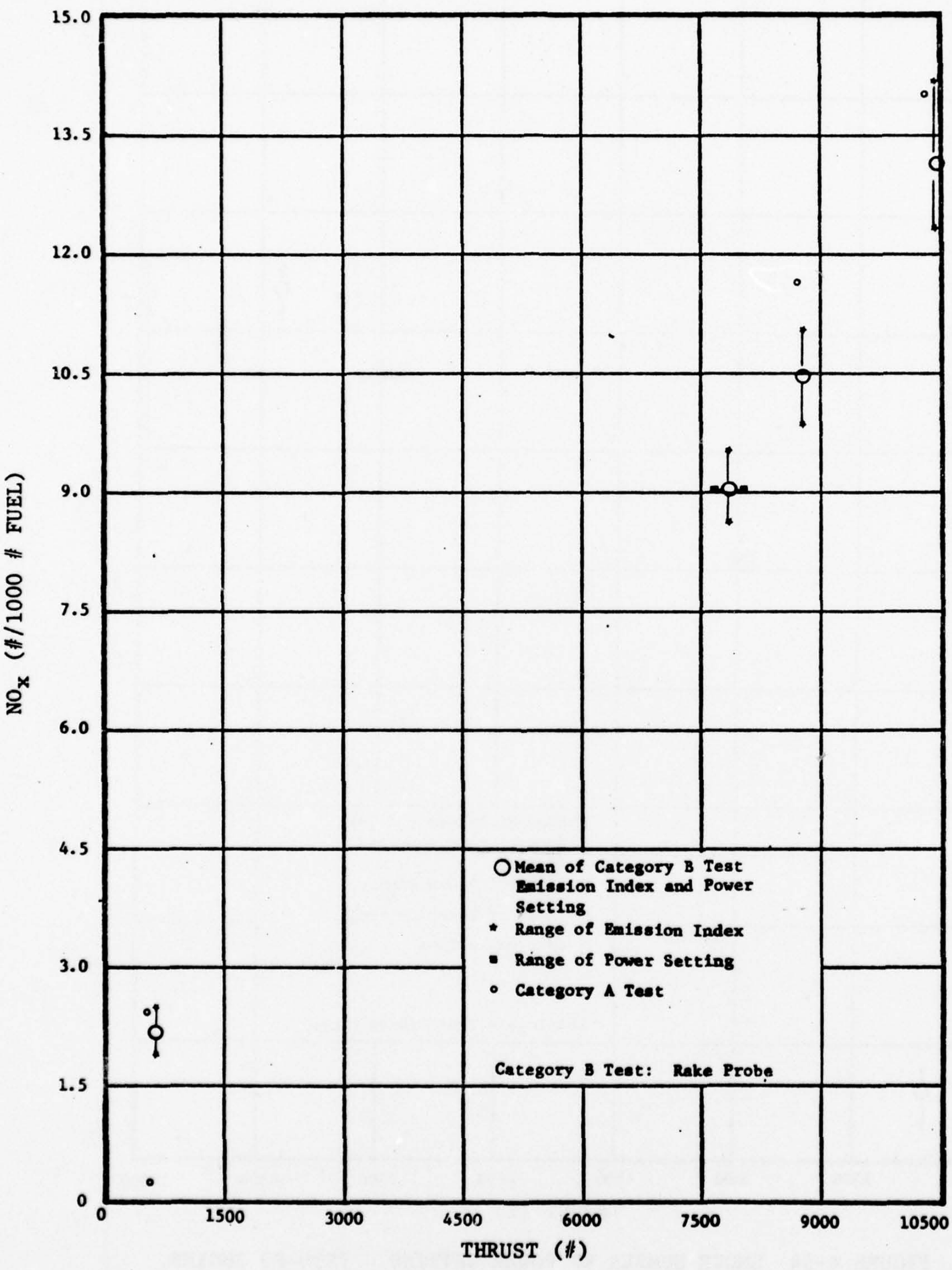


FIGURE 4-53 NO_x EMISSION INDEX VS POWER SETTING. TF30-P3 ENGINE.

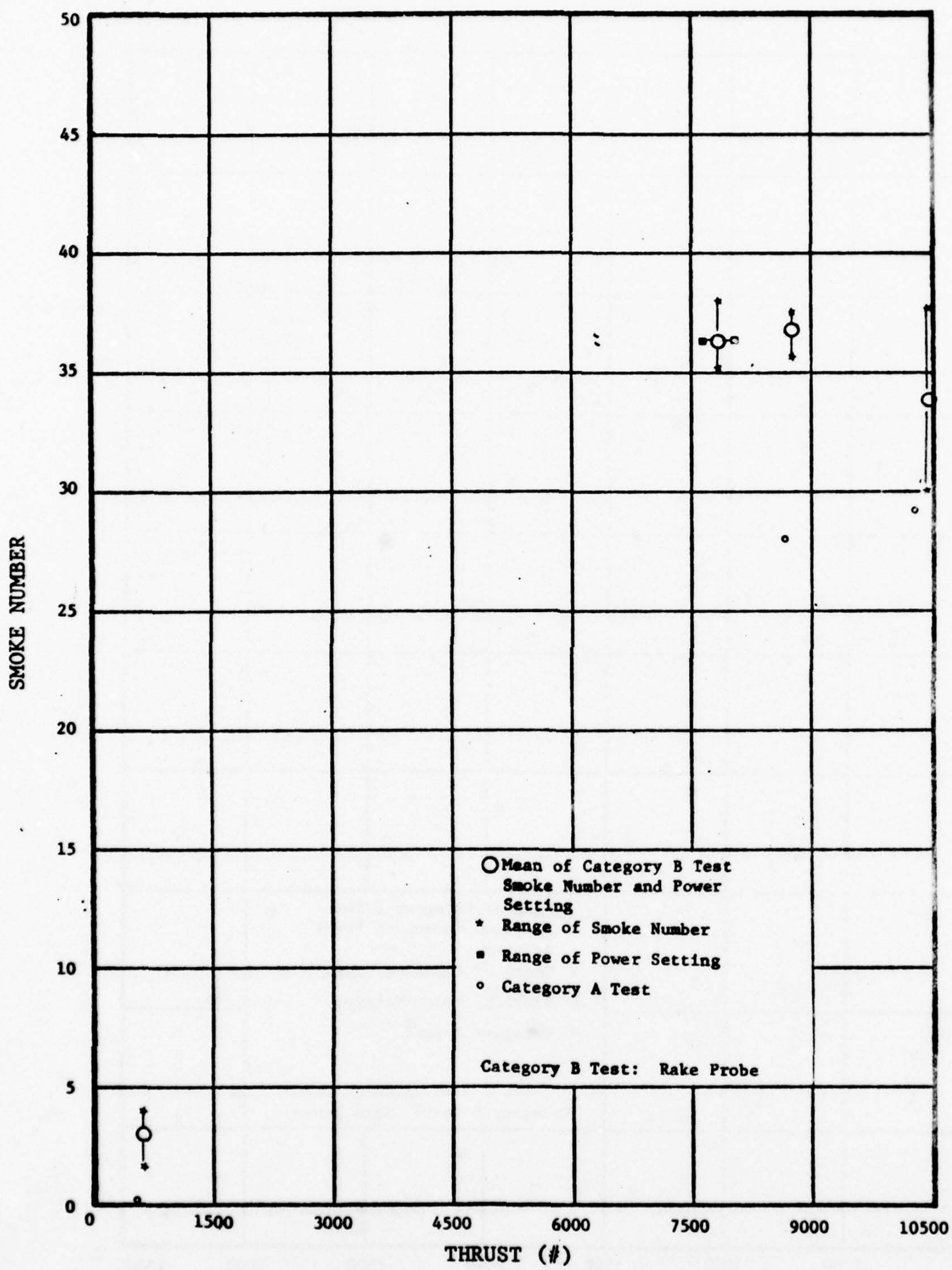


FIGURE 4-54 SMOKE NUMBER VS POWER SETTING. TF30-P3 ENGINE.

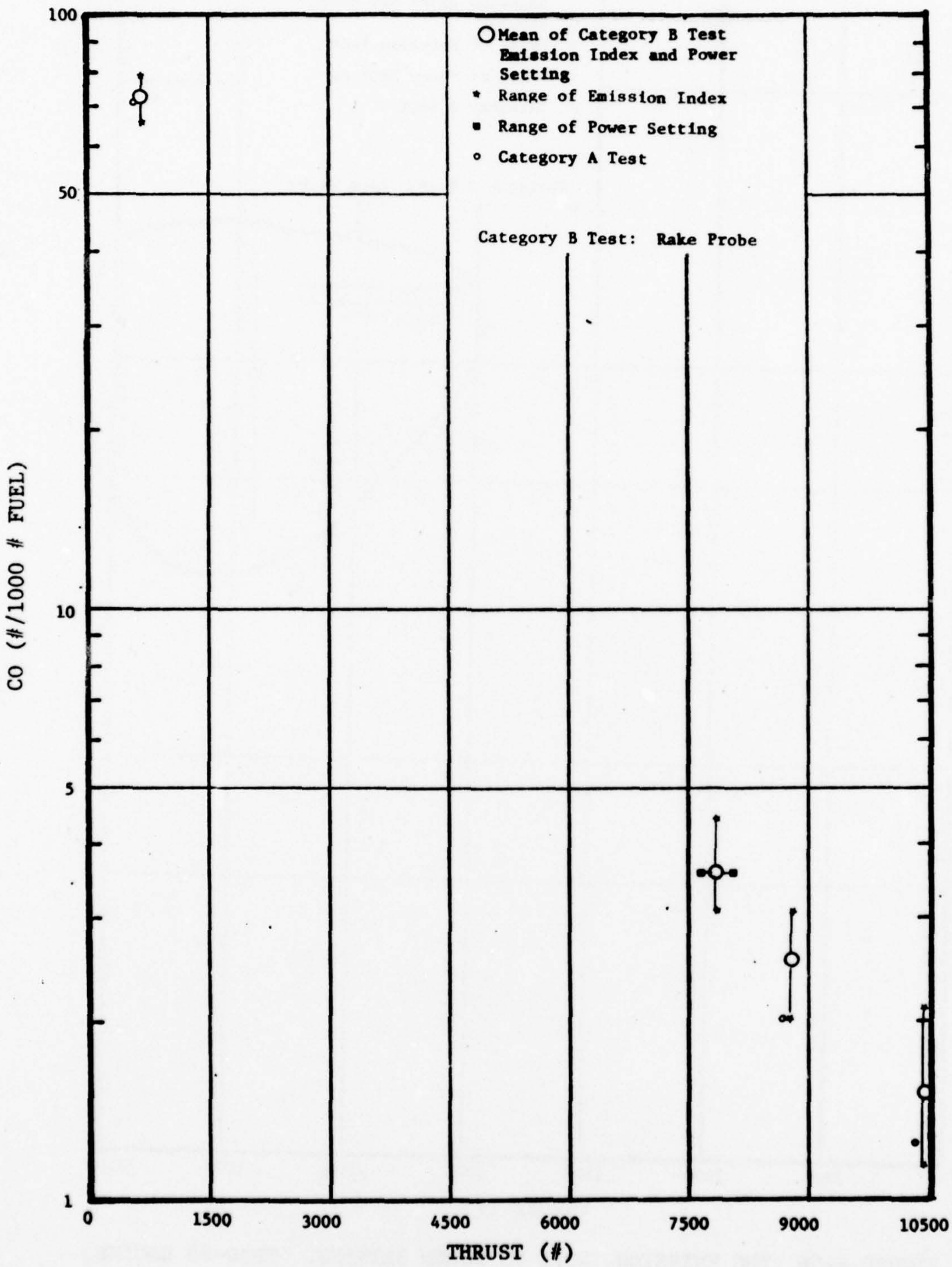


FIGURE 4-55 CO EMISSION INDEX VS POWER SETTING. TF30-P3 ENGINE.

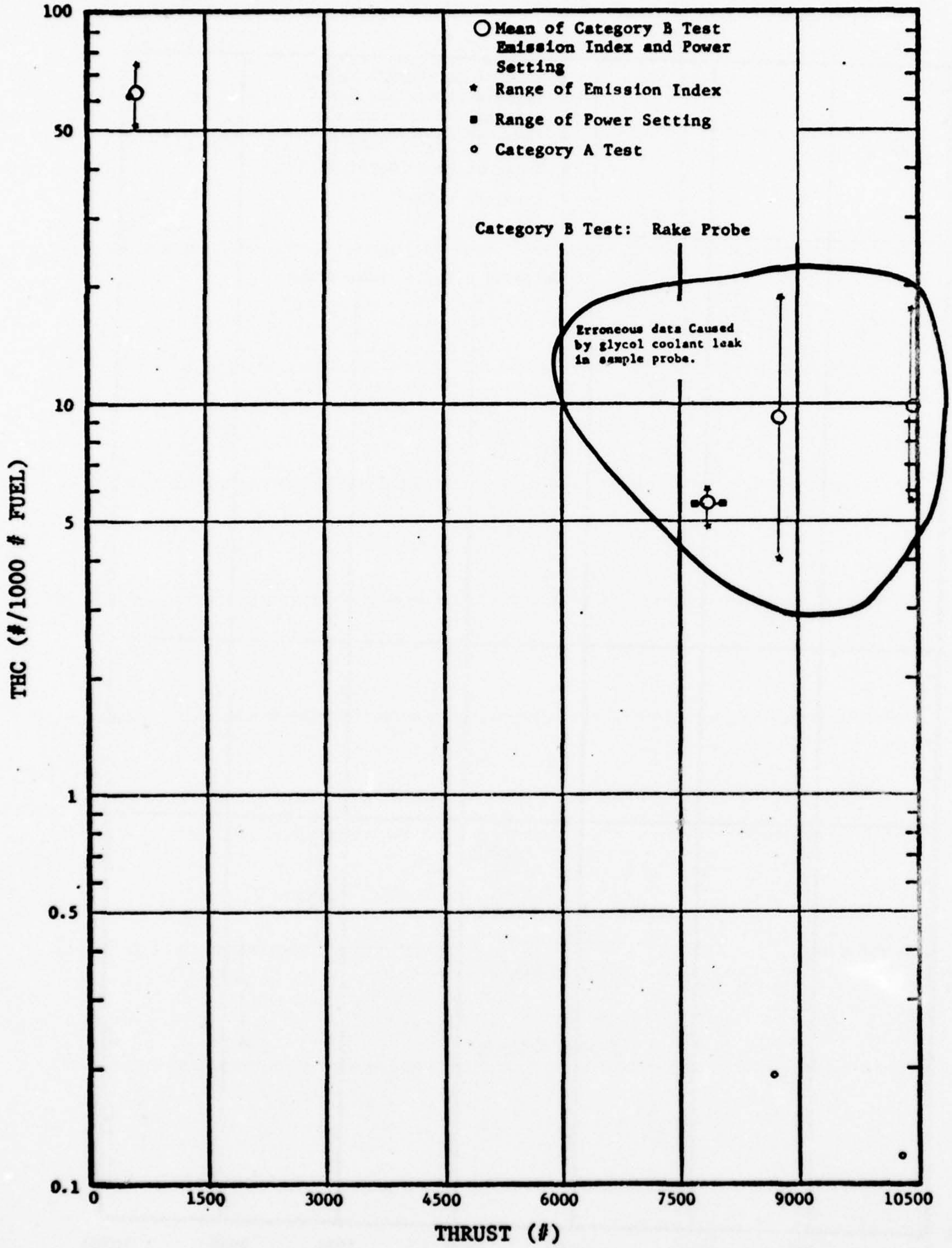


FIGURE 4-56 THC EMISSION INDEX VS POWER SETTING. TF30-P3 ENGINE.

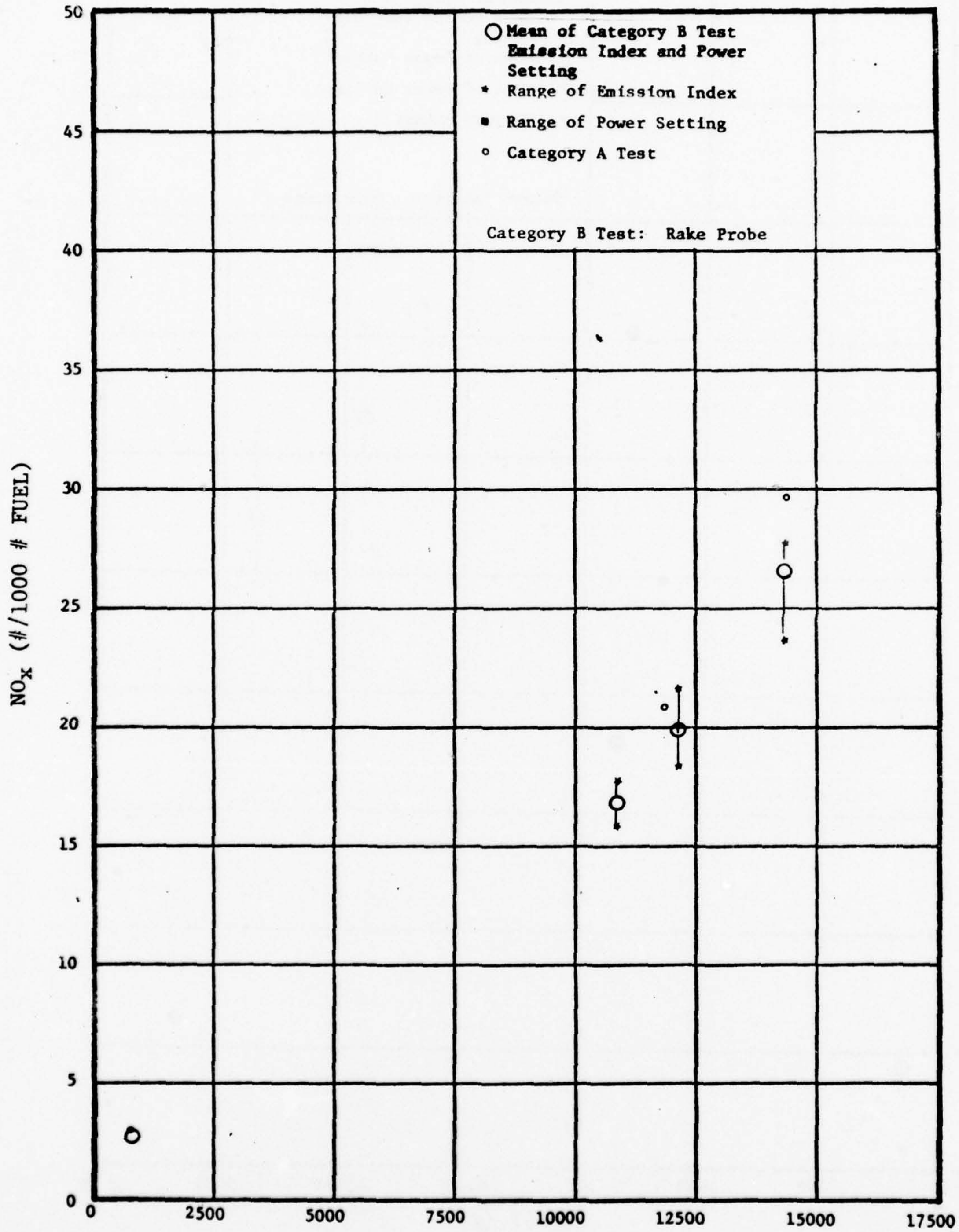


FIGURE 4-57 NO_x EMISSION INDEX VS POWER SETTING. TF30-P100 ENGINE.

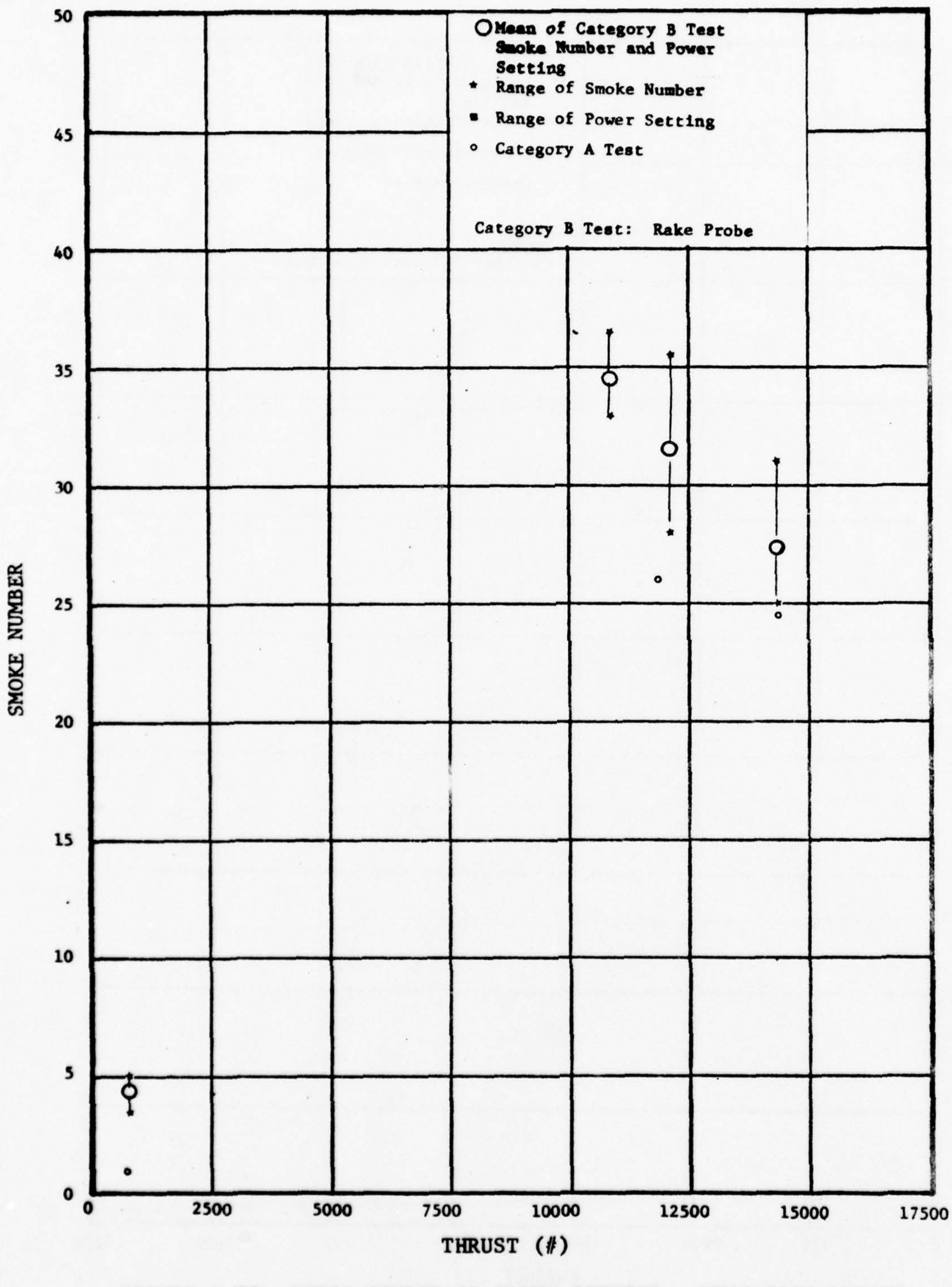


FIGURE 4-58 SMOKE NUMBER VS POWER SETTING. TF30-P100 ENGINE.

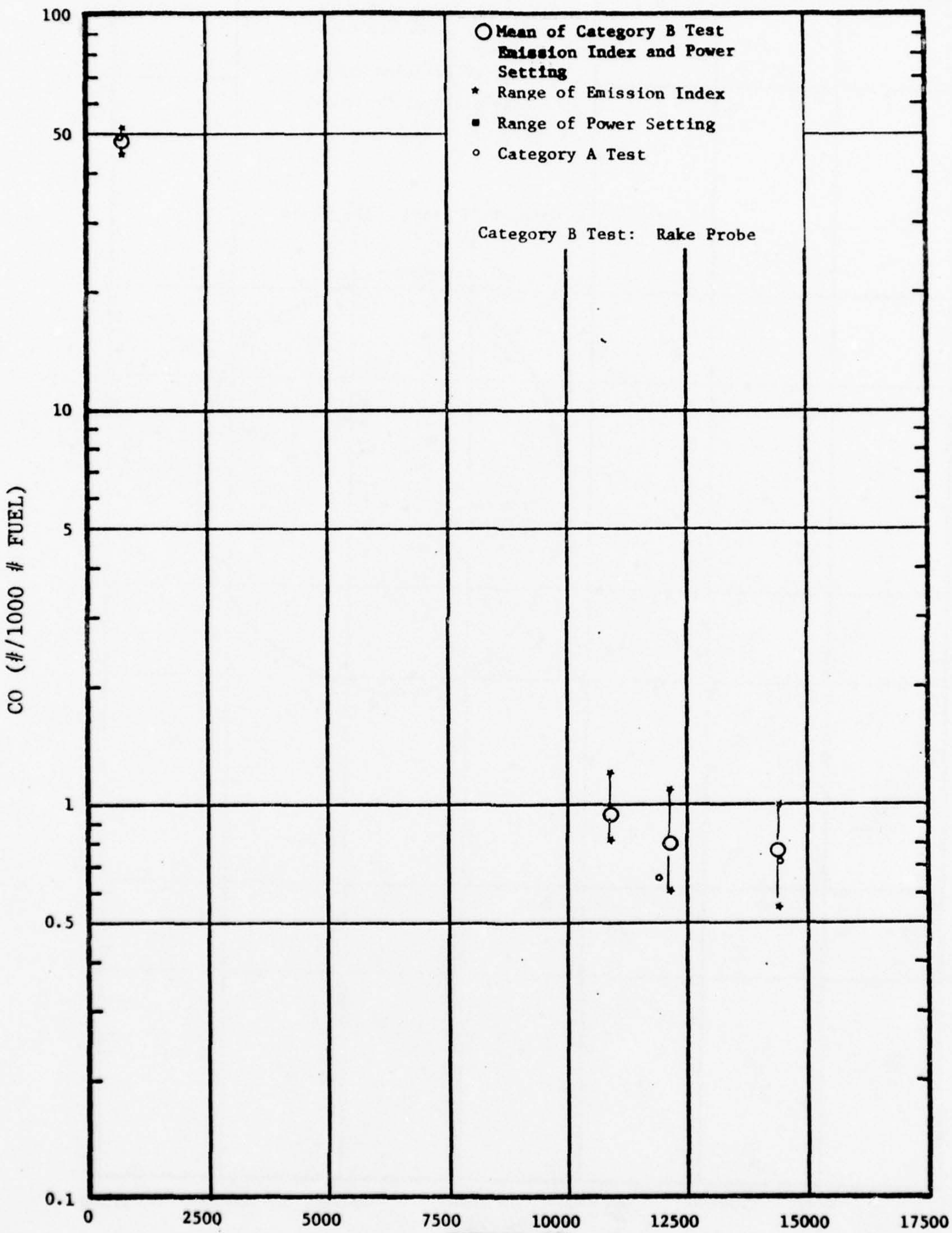


FIGURE 4-59 CO EMISSION INDEX VS POWER SETTING. TF30-P100 ENGINE.

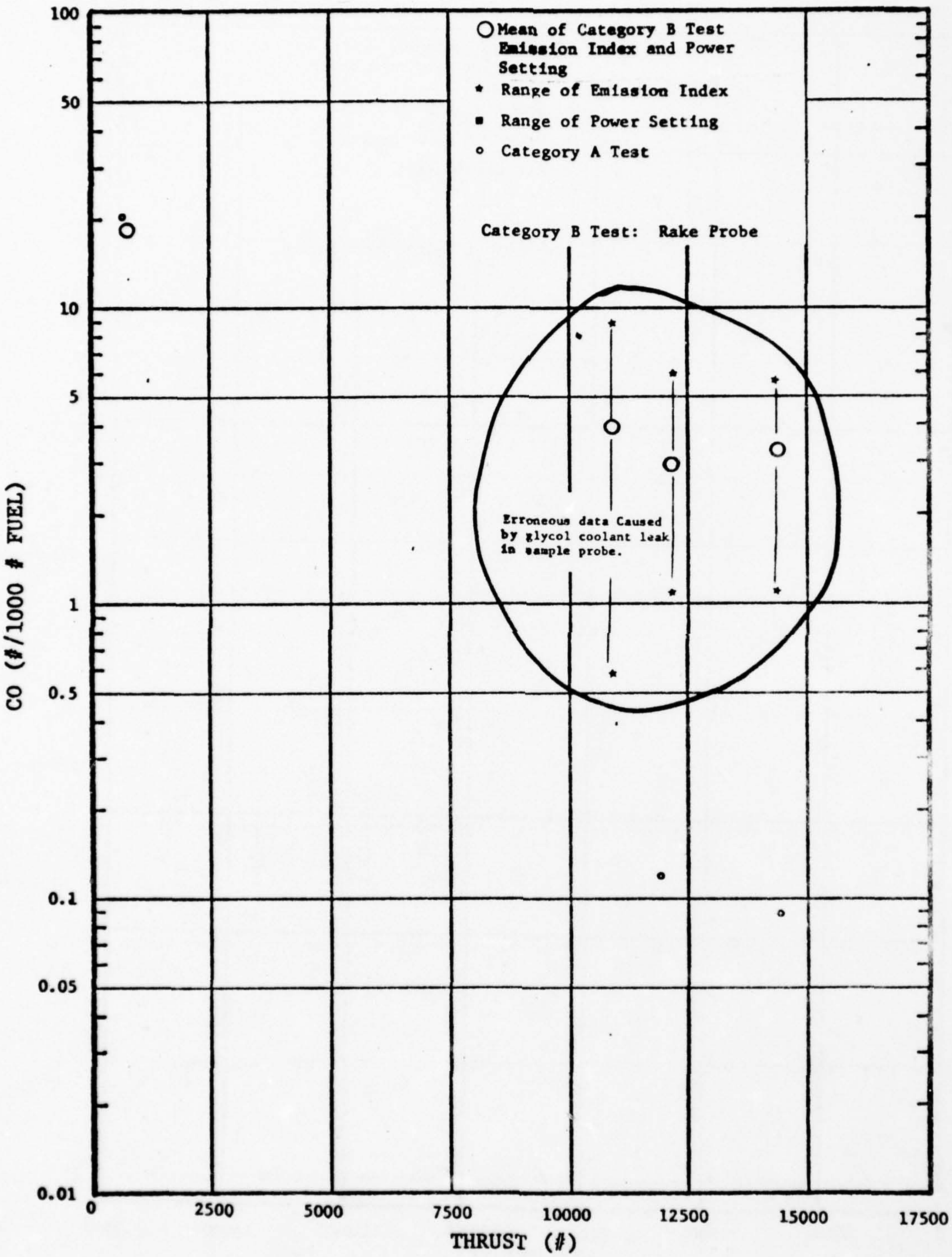


FIGURE 4-60 THC EMISSION INDEX VS POWER SETTING. TF30-P100 ENGINE.

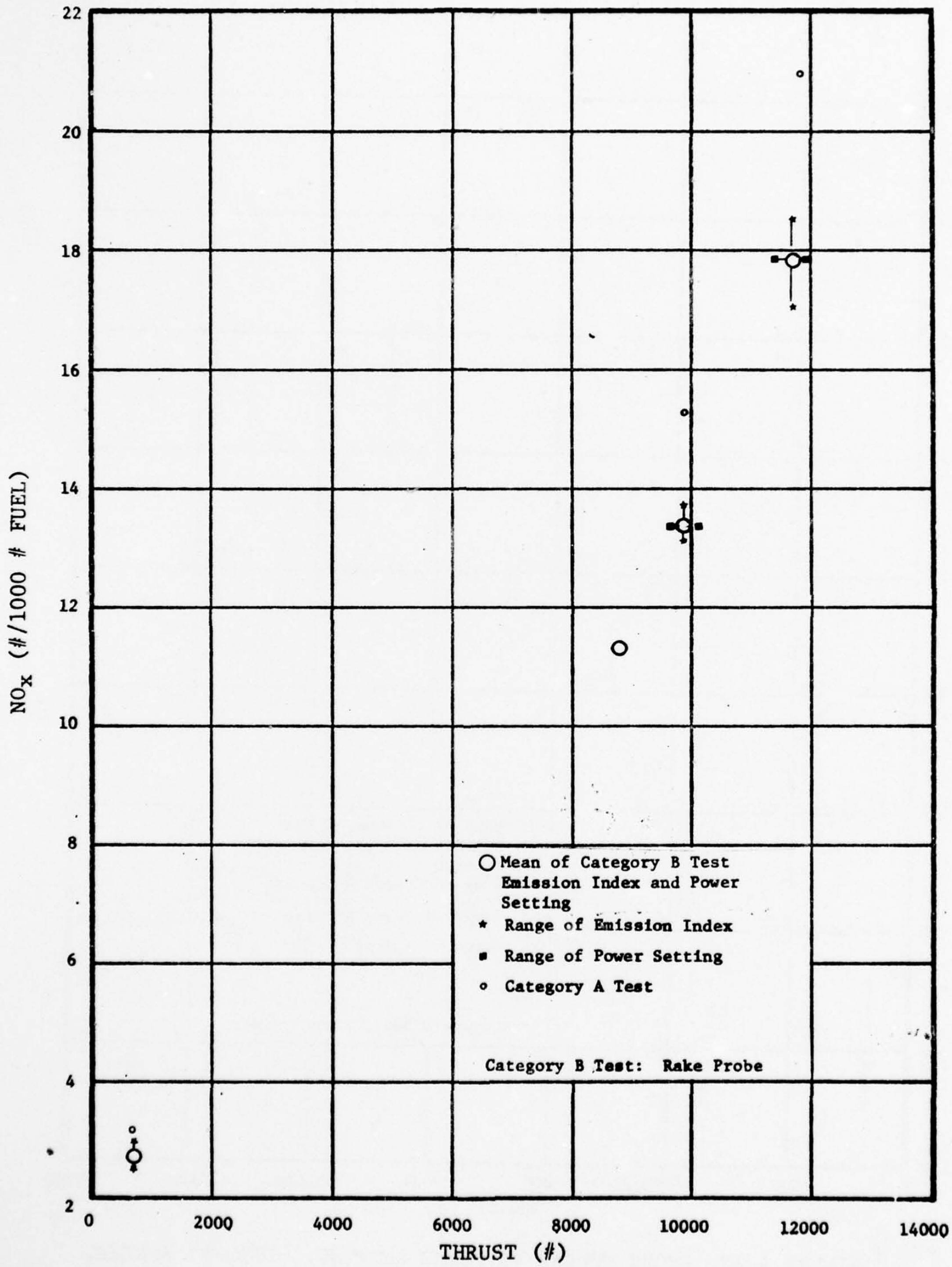


FIGURE 4-61 NO_x EMISSION INDEX VS POWER SETTING. TF30-P7 ENGINE.

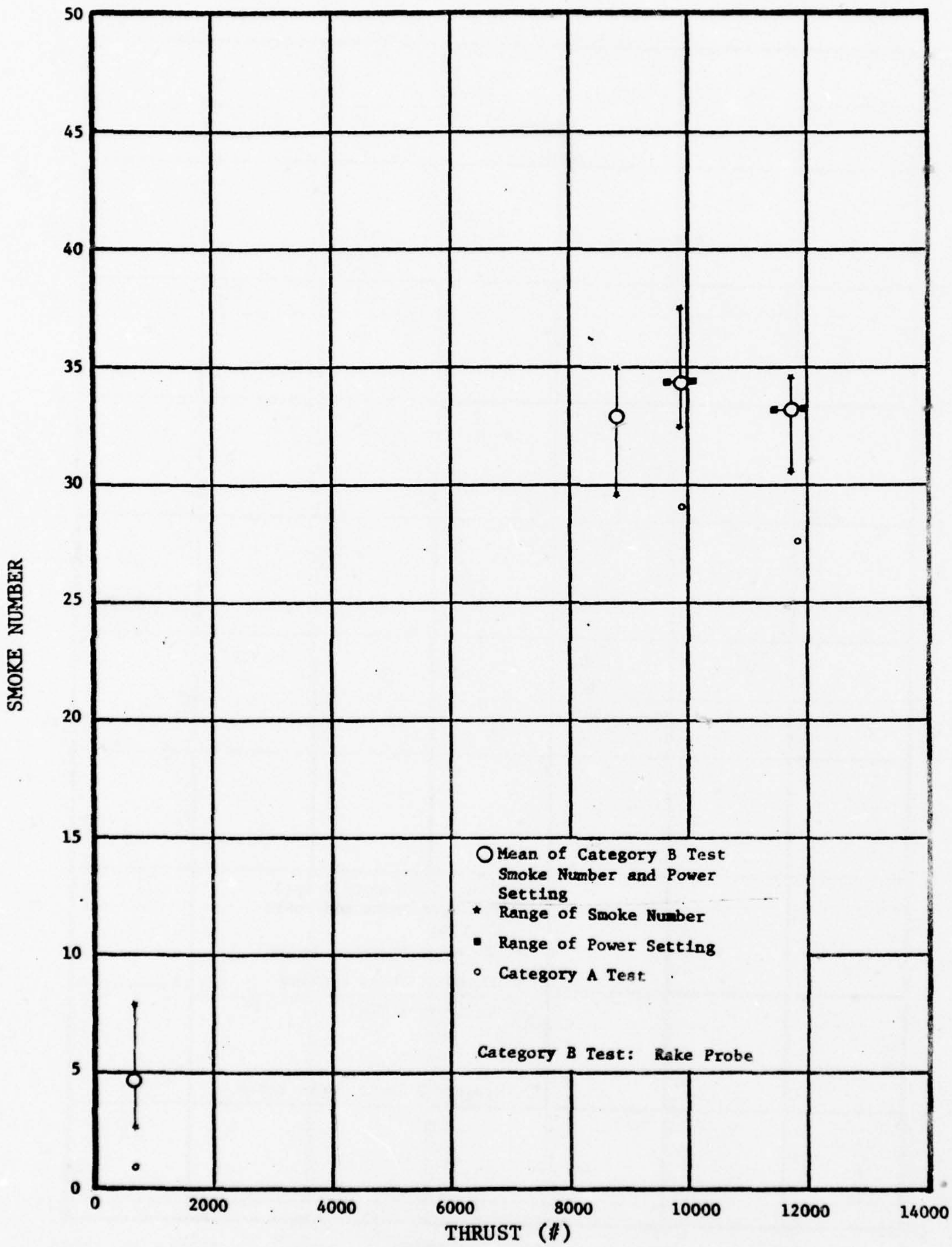


FIGURE 4-62 SMOKE NUMBER VS POWER SETTING. TF30-P7 ENGINE.

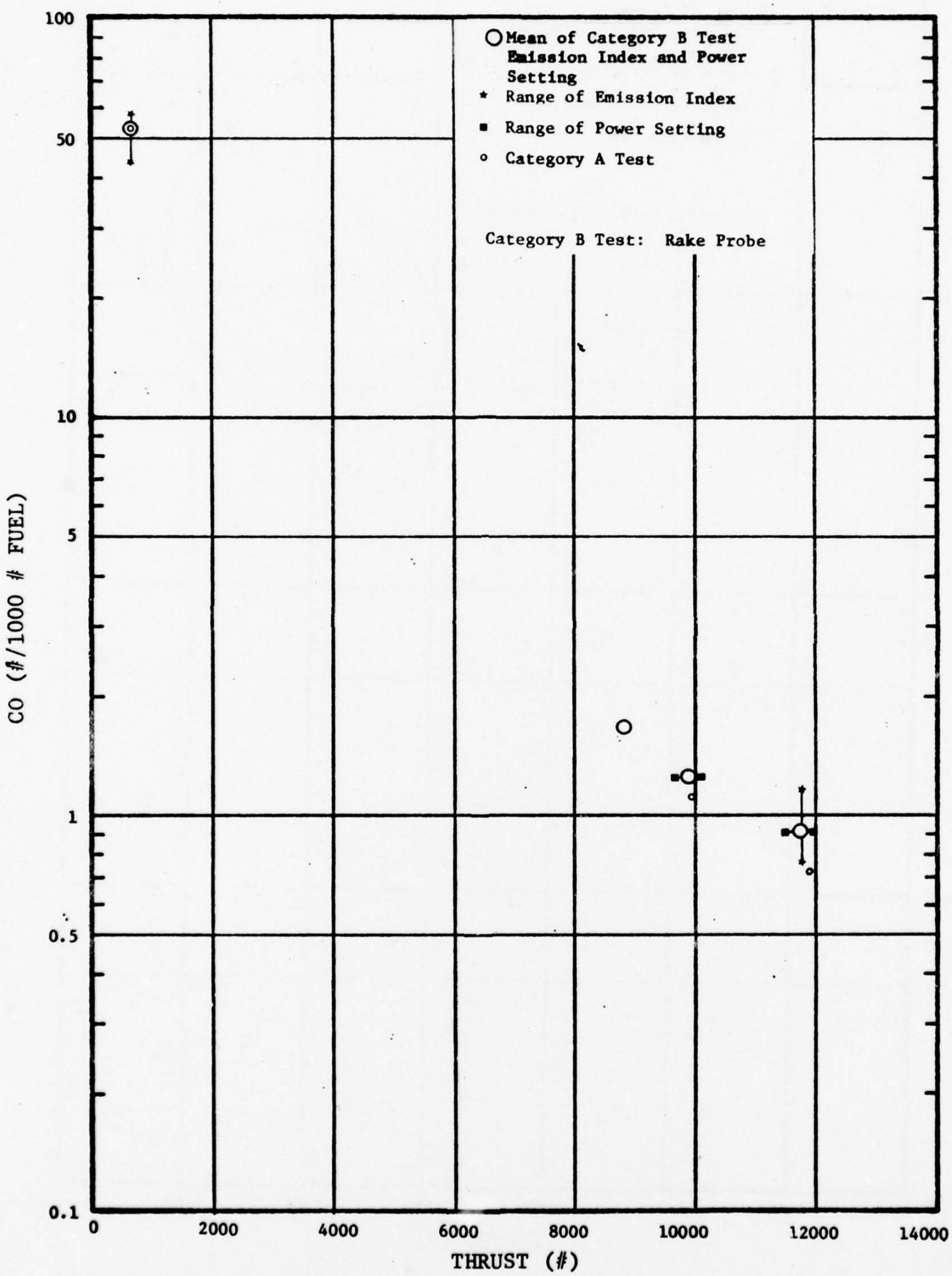


FIGURE 4-63 CO EMISSION INDEX VS POWER SETTING. TF30-P7 ENGINE.

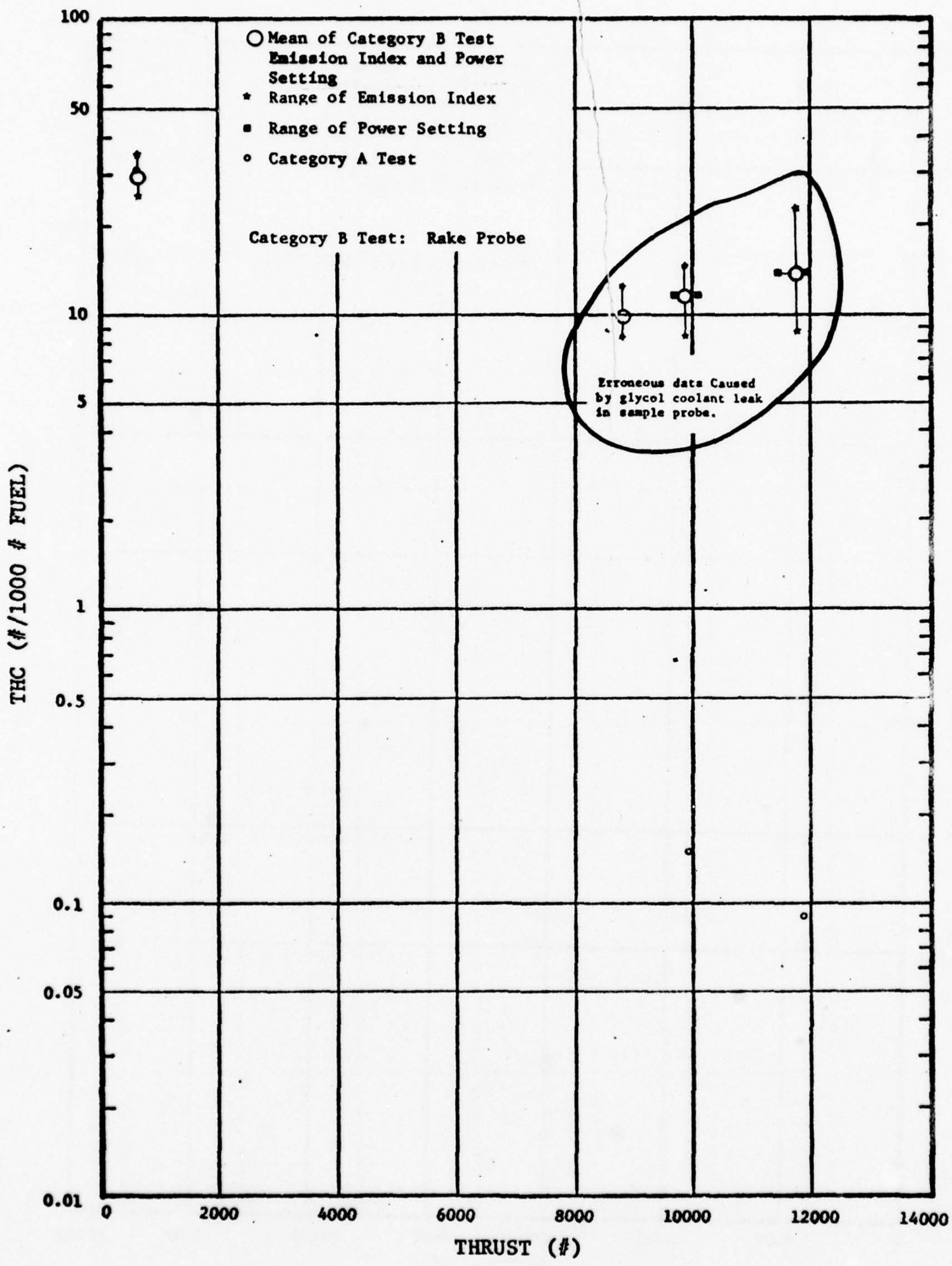


FIGURE 4-64 THC EMISSION INDEX VS POWER SETTING. TF30-P7 ENGINE.

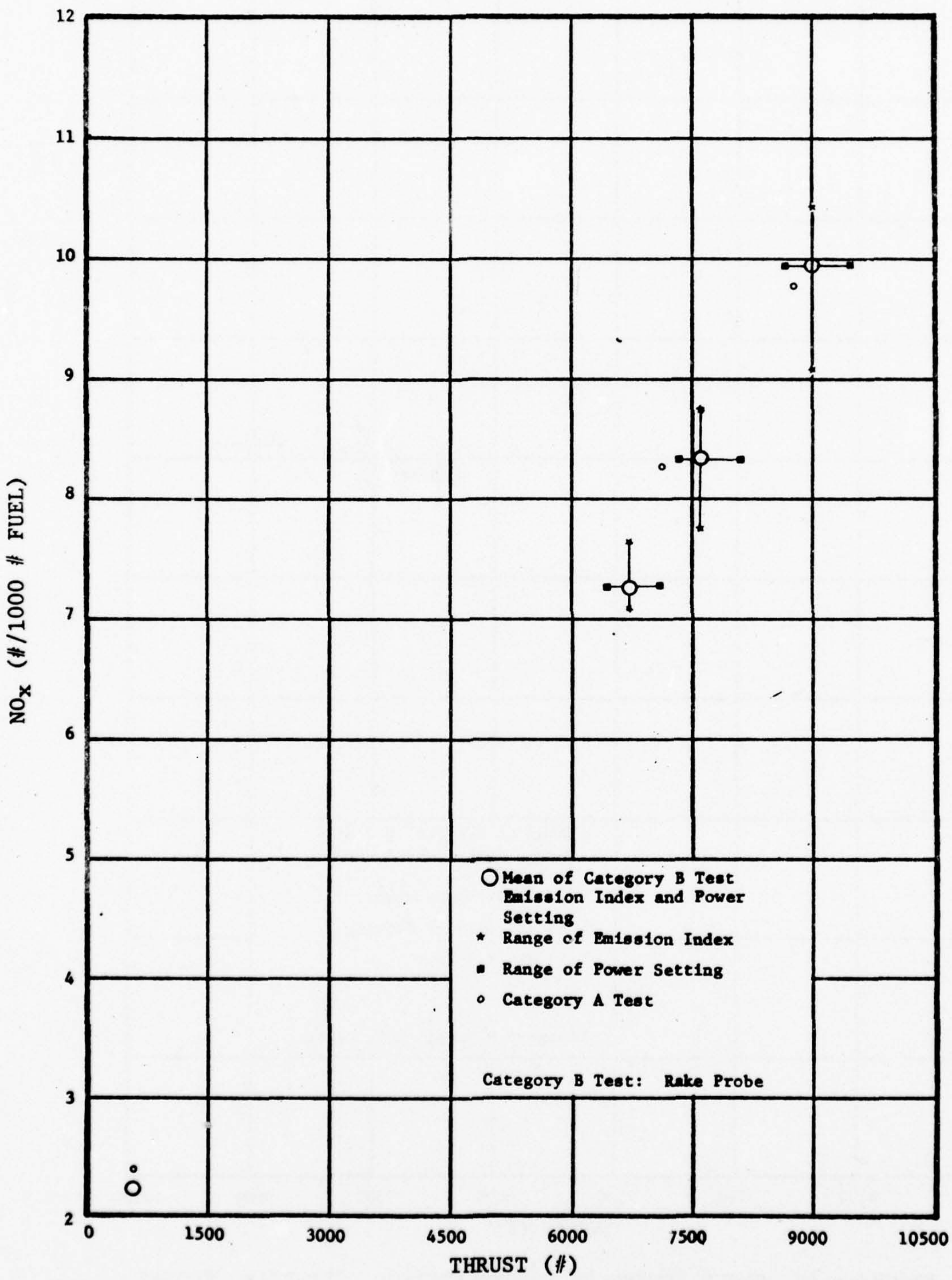


FIGURE 4-65 NO_x EMISSION INDEX VS POWER SETTING. J57-P21B ENGINE.

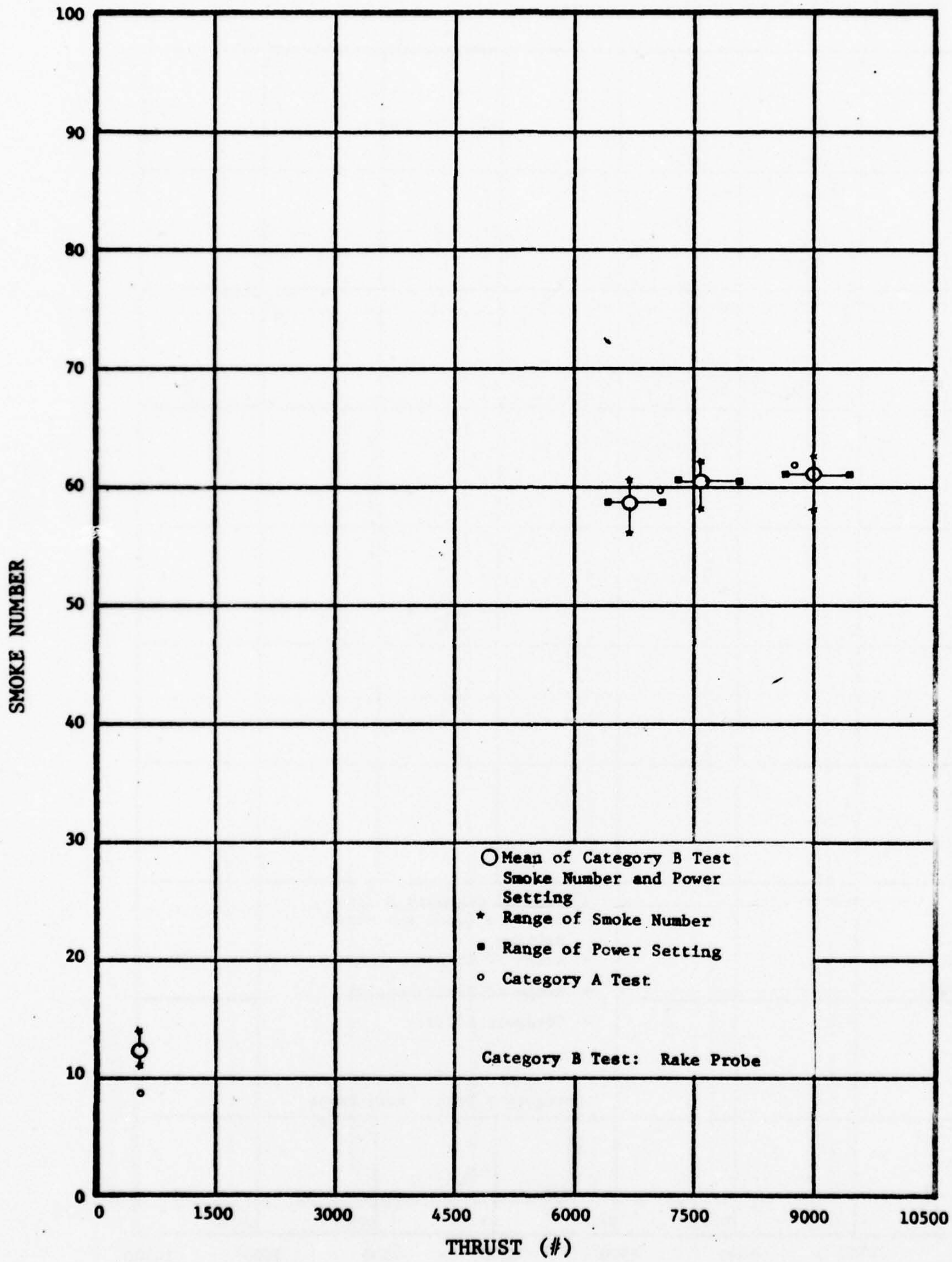


FIGURE 4-66 SMOKE NUMBER VS POWER SETTING. J57-P21B ENGINE.

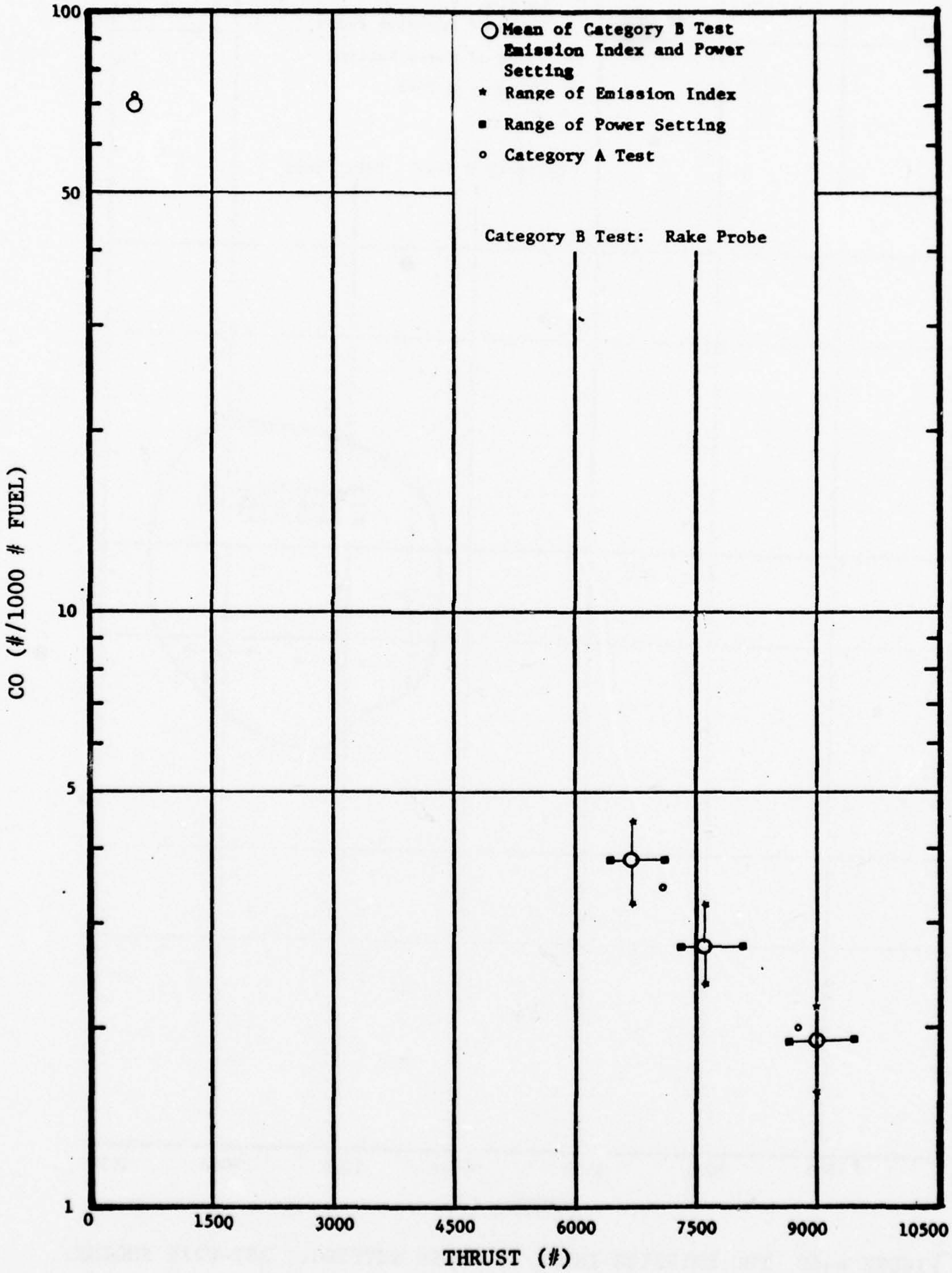


FIGURE 4-67 CO EMISSION INDEX VS POWER SETTING. J57-P21B ENGINE.

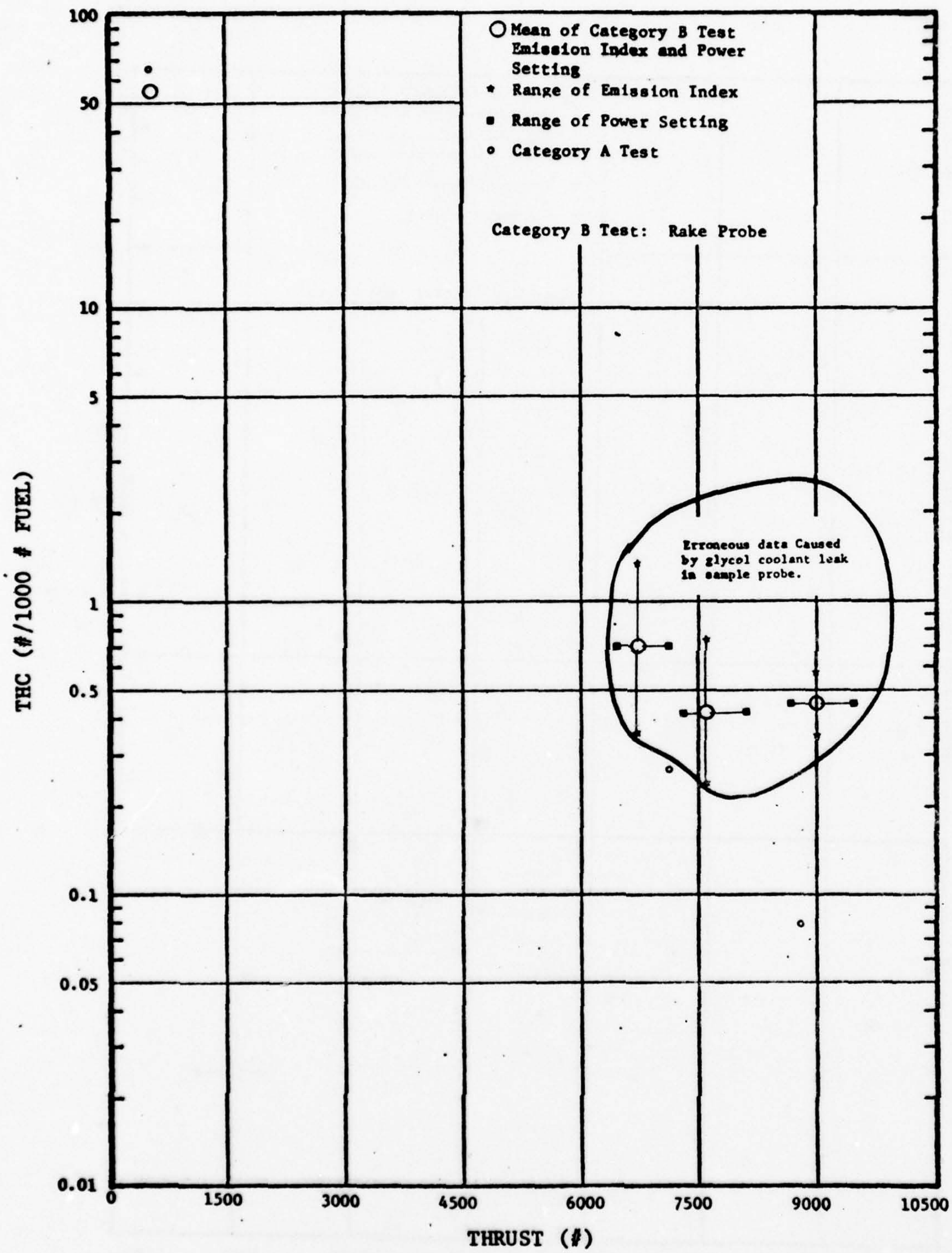


FIGURE 4-68 THC EMISSION INDEX VS POWER SETTING. J57-P21B ENGINE.

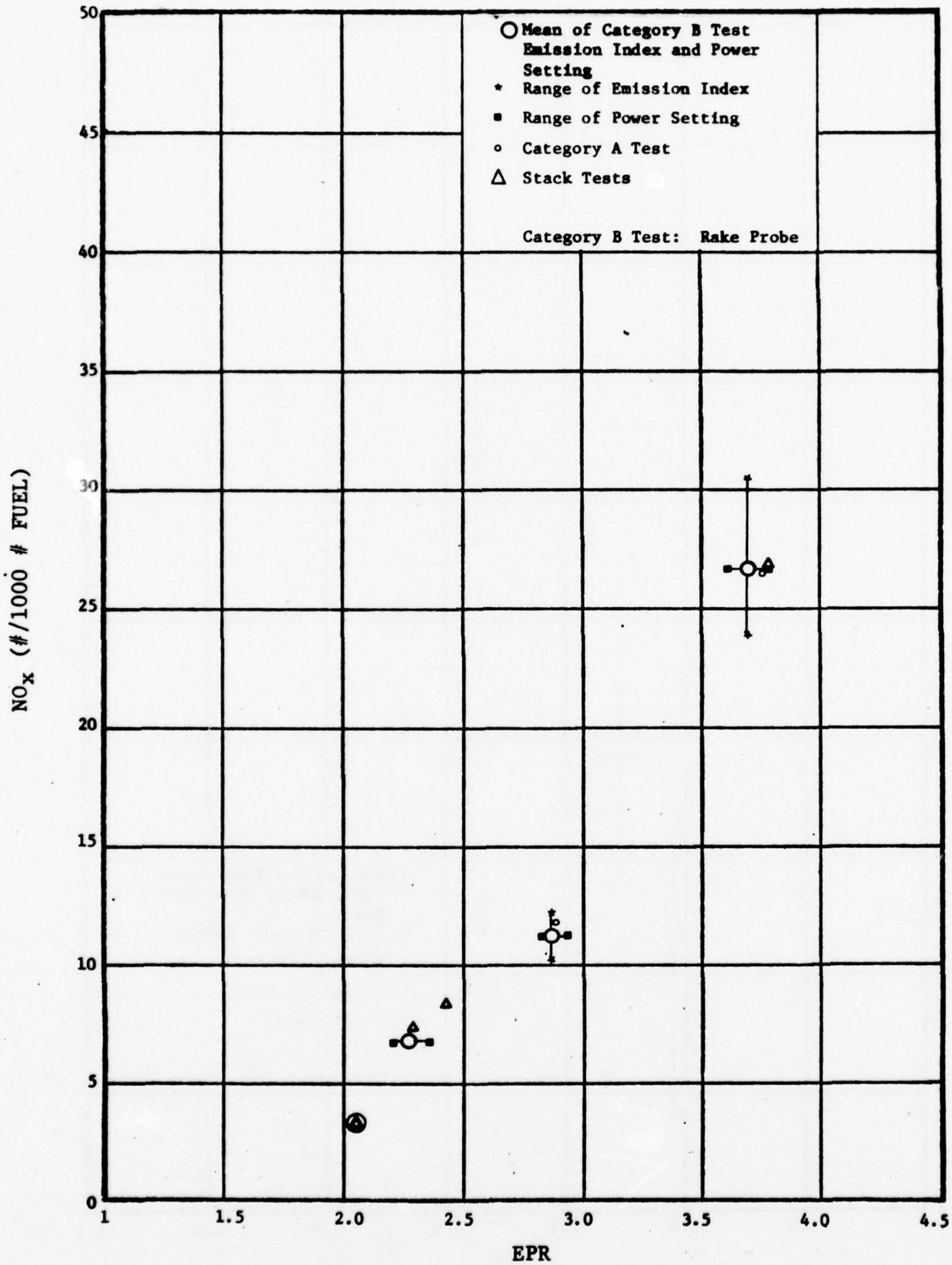


FIGURE 4-69 NO_x EMISSION INDEX VS POWER SETTING. F100-PW100 ENGINE.

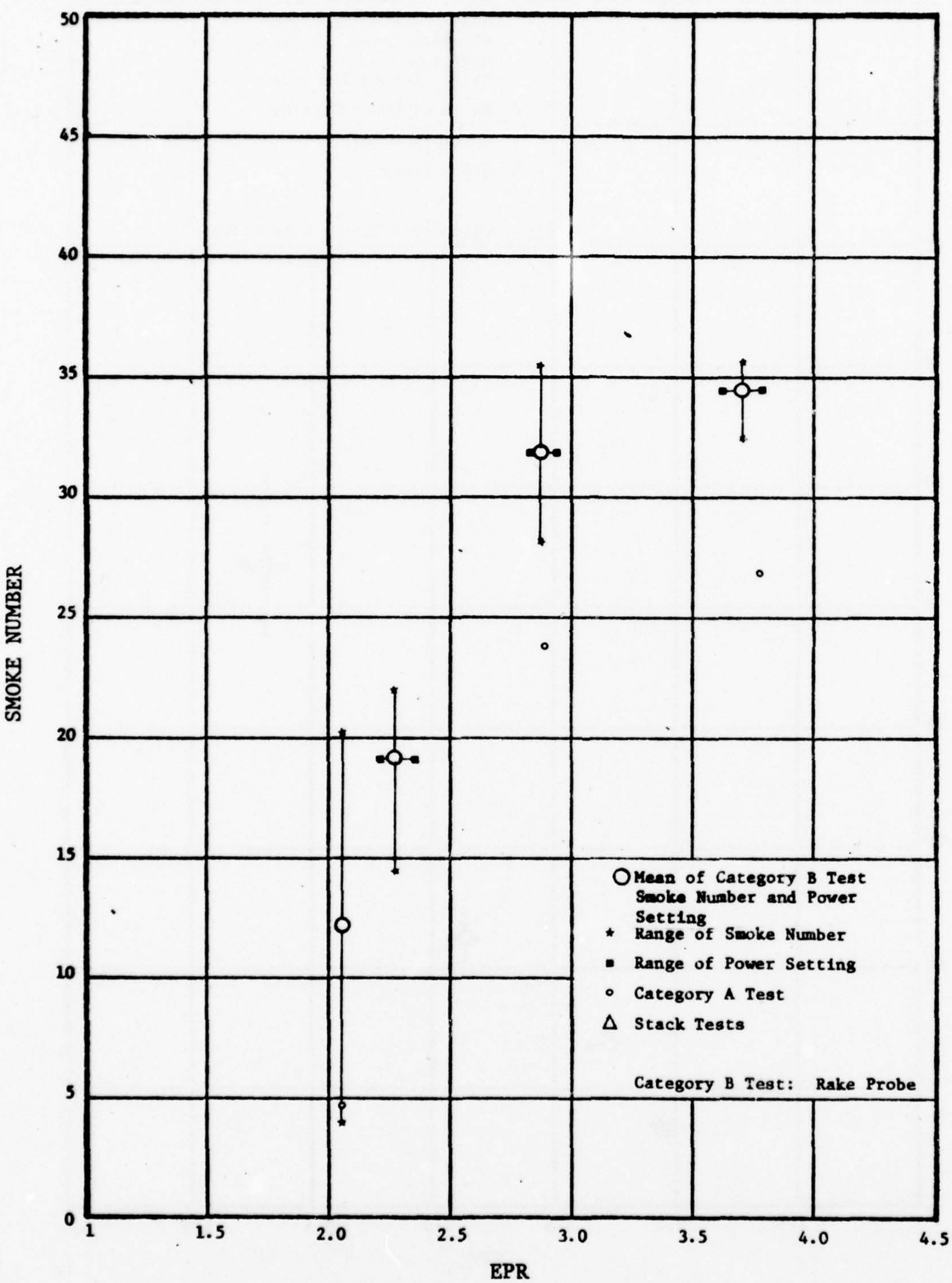


FIGURE 4-70 SMOKE NUMBER VS POWER SETTING. F100-PW100 ENGINE.

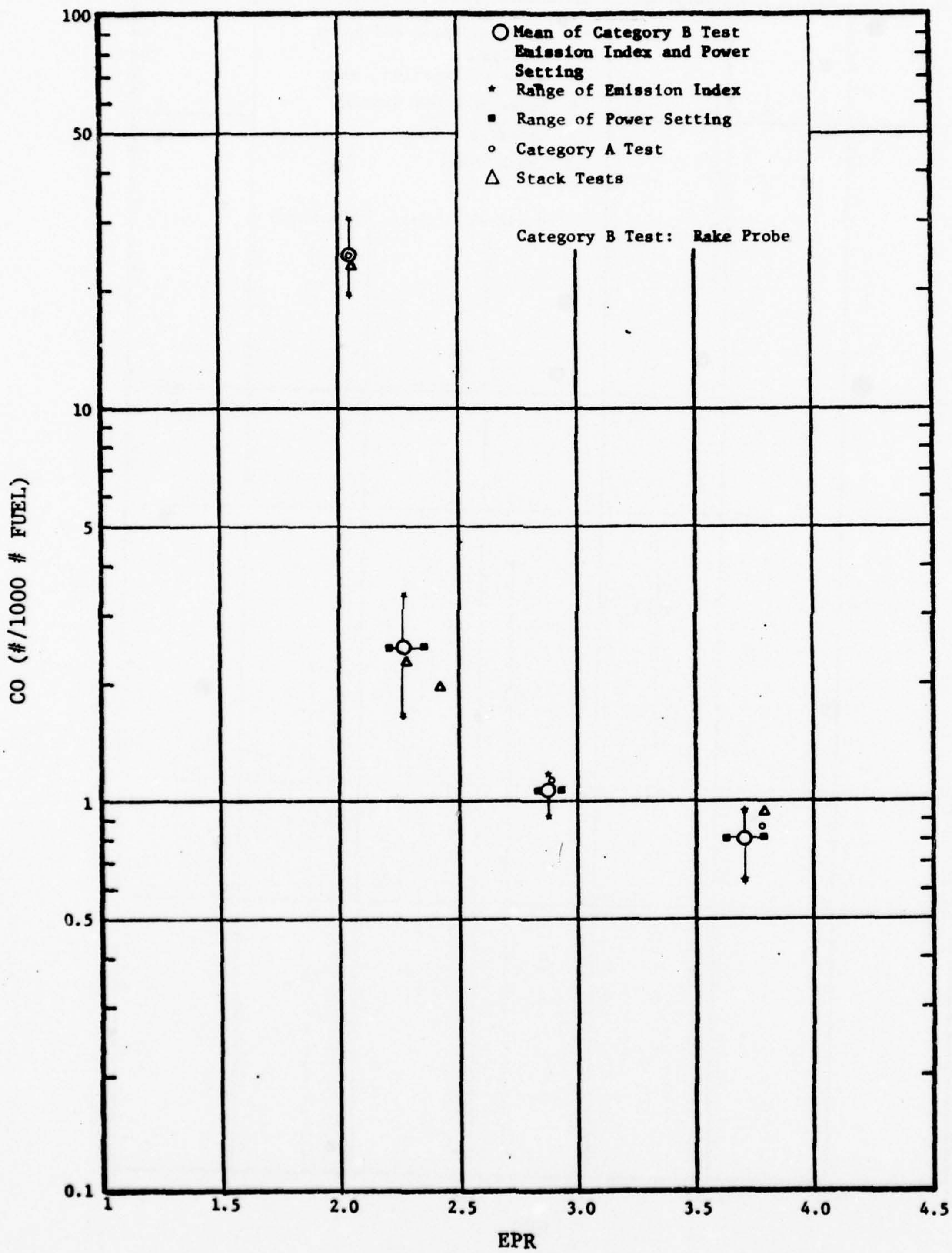


FIGURE 4-71 CO EMISSION INDEX VS POWER SETTING. F100-PW100 ENGINE.

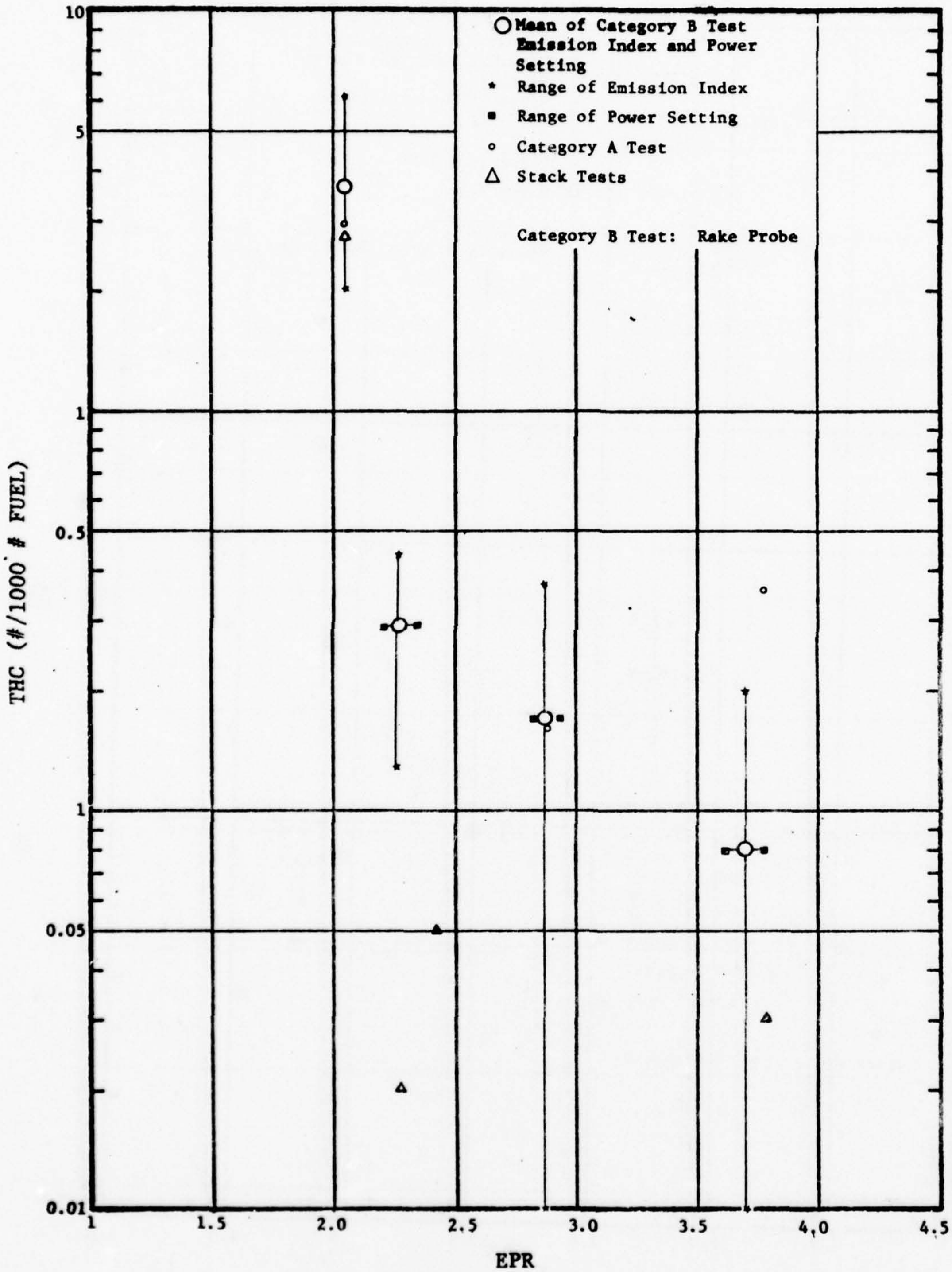


FIGURE 4-72 THC EMISSION INDEX VS POWER SETTING. F100-PW100 ENGINE.

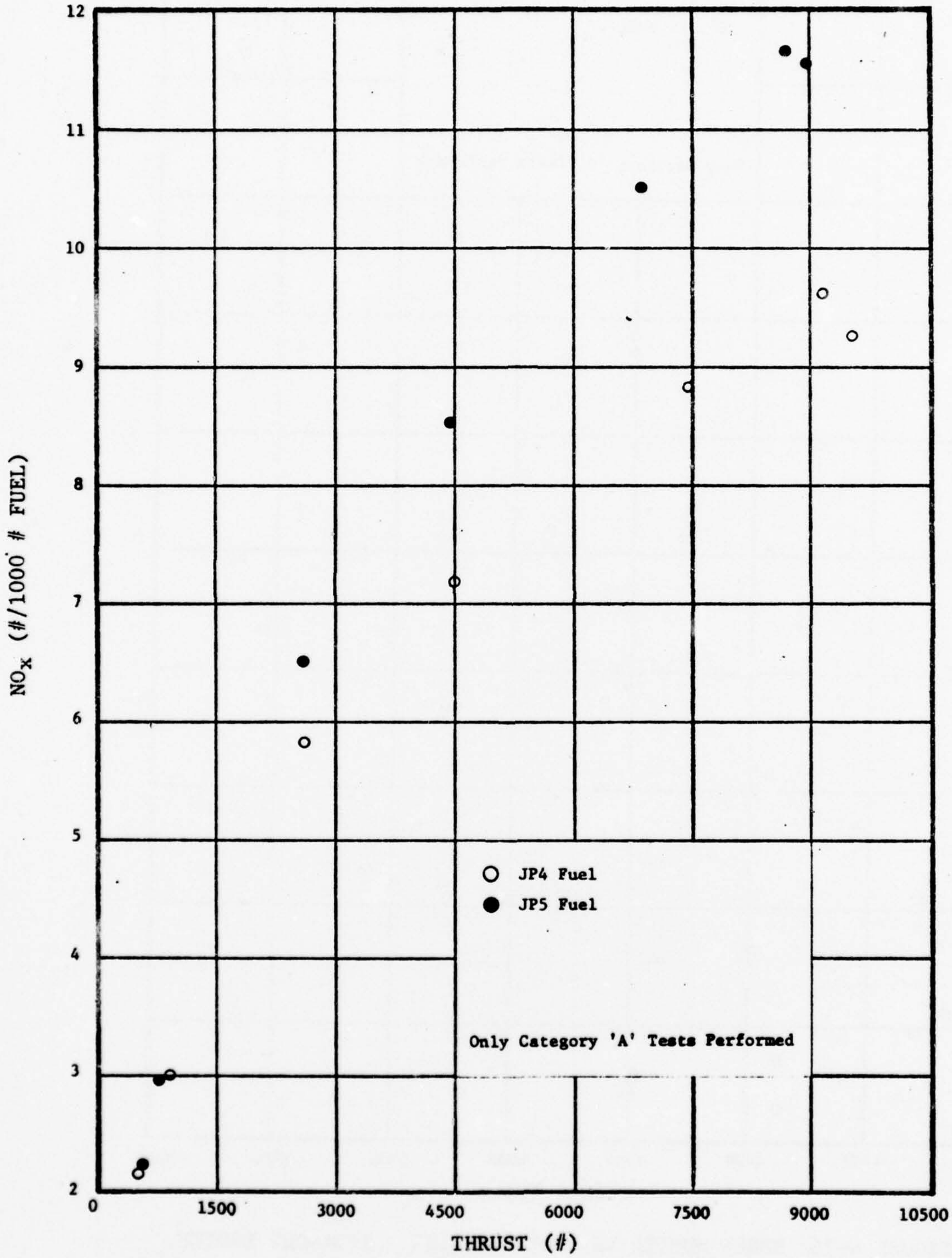


FIGURE 4-73 NO_x EMISSION INDEX VS POWER SETTING. TF34-DEV ENGINE.

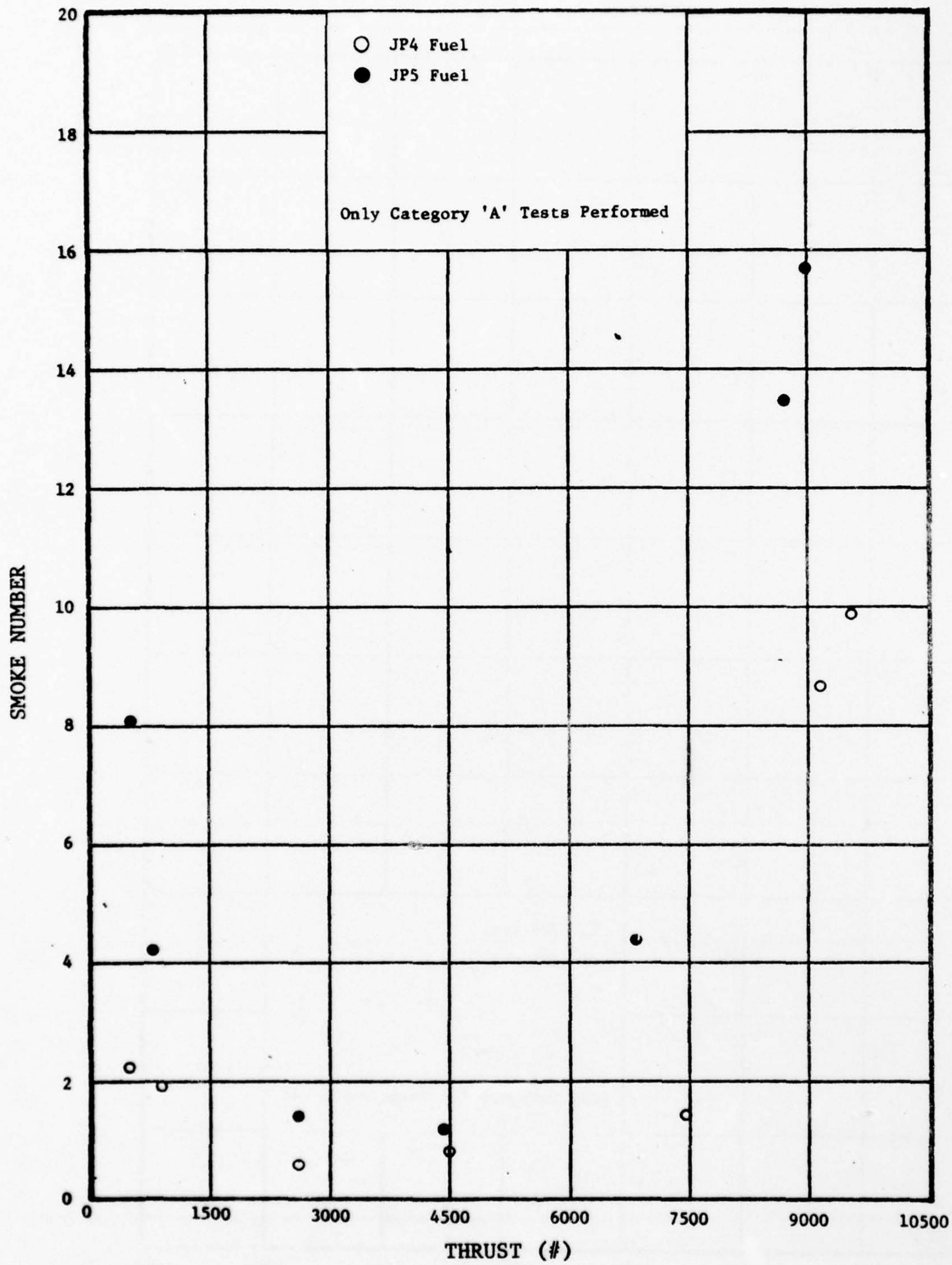


FIGURE 4-74 SMOKE NUMBER VS POWER SETTING. TF34-DEV ENGINE.

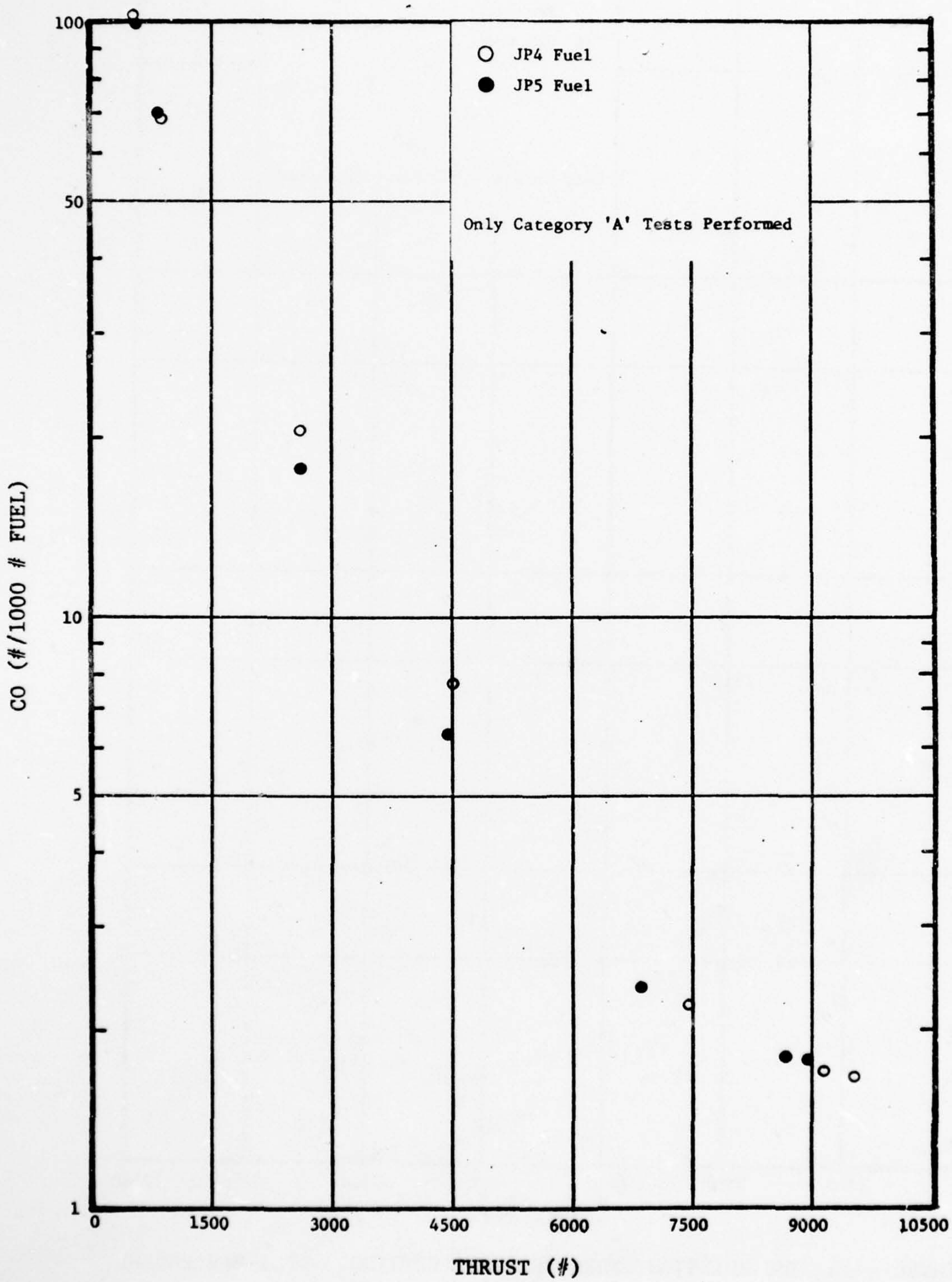


FIGURE 4-75 CO EMISSION INDEX VS POWER SETTING. TF34-DEV ENGINE.

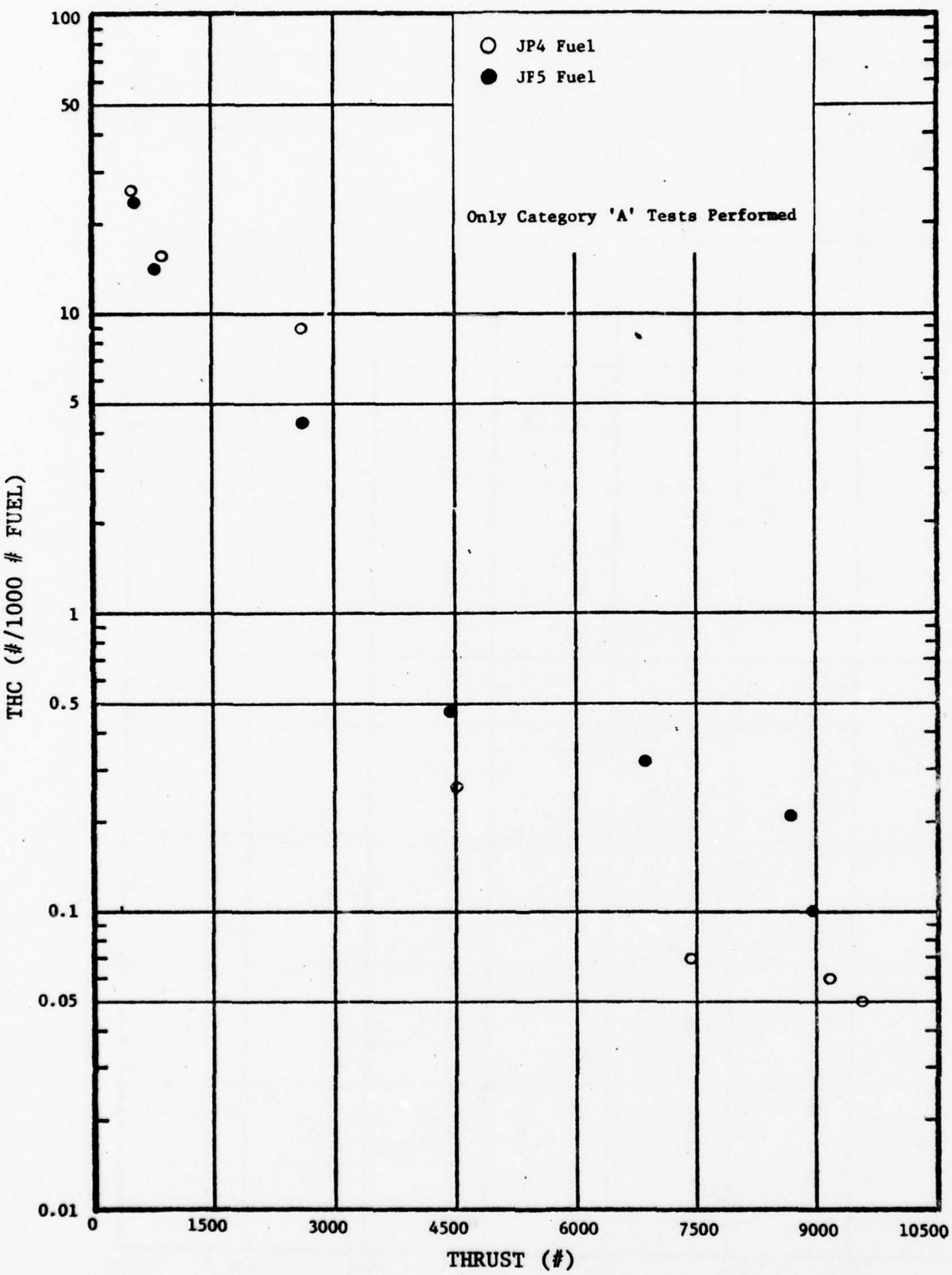


FIGURE 4-76 THC EMISSION INDEX VS POWER SETTING. TF34-DEV ENGINE.

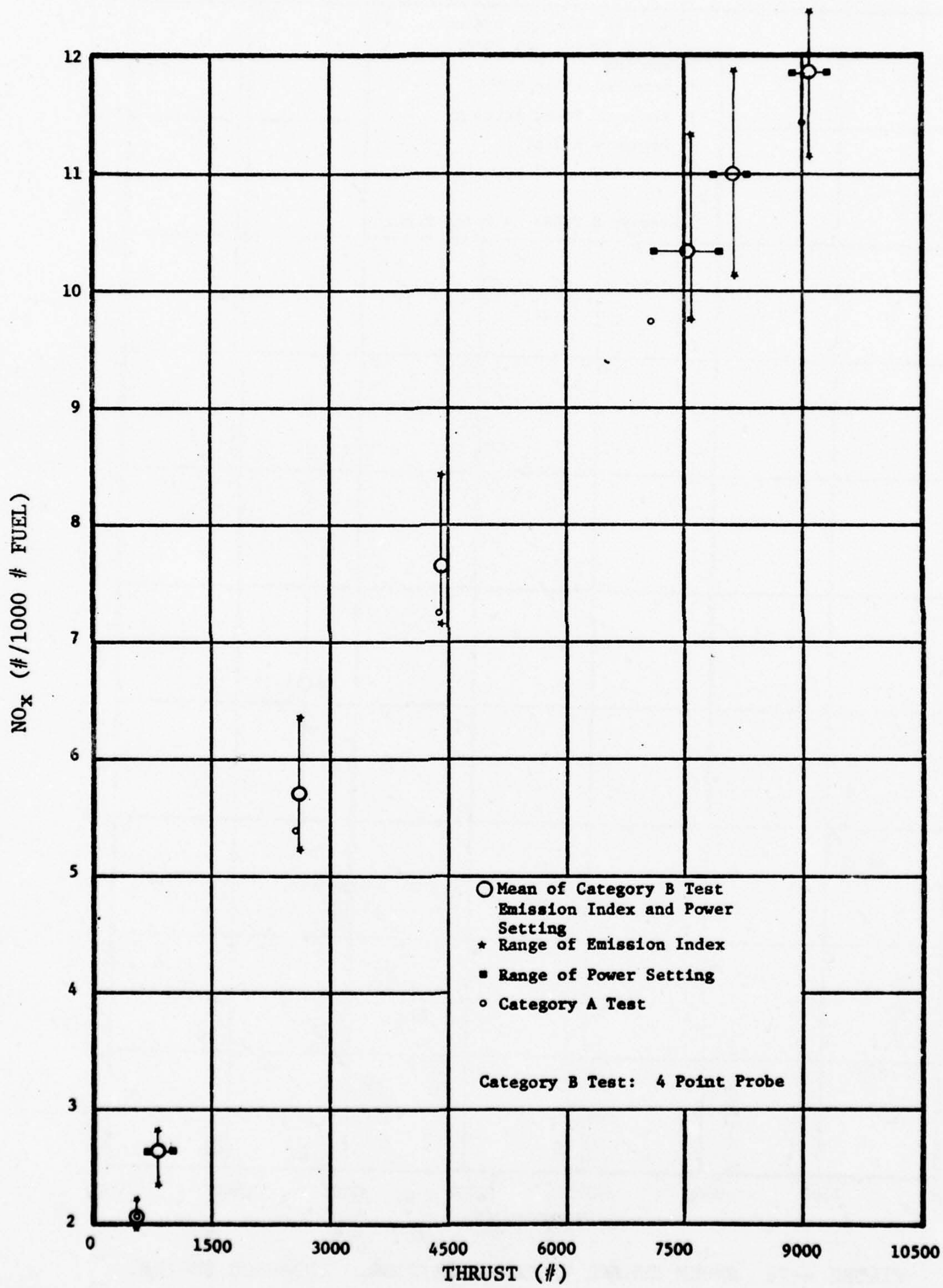


FIGURE 4-77 NO_x EMISSION INDEX VS POWER SETTING. TF34-100 ENGINE.

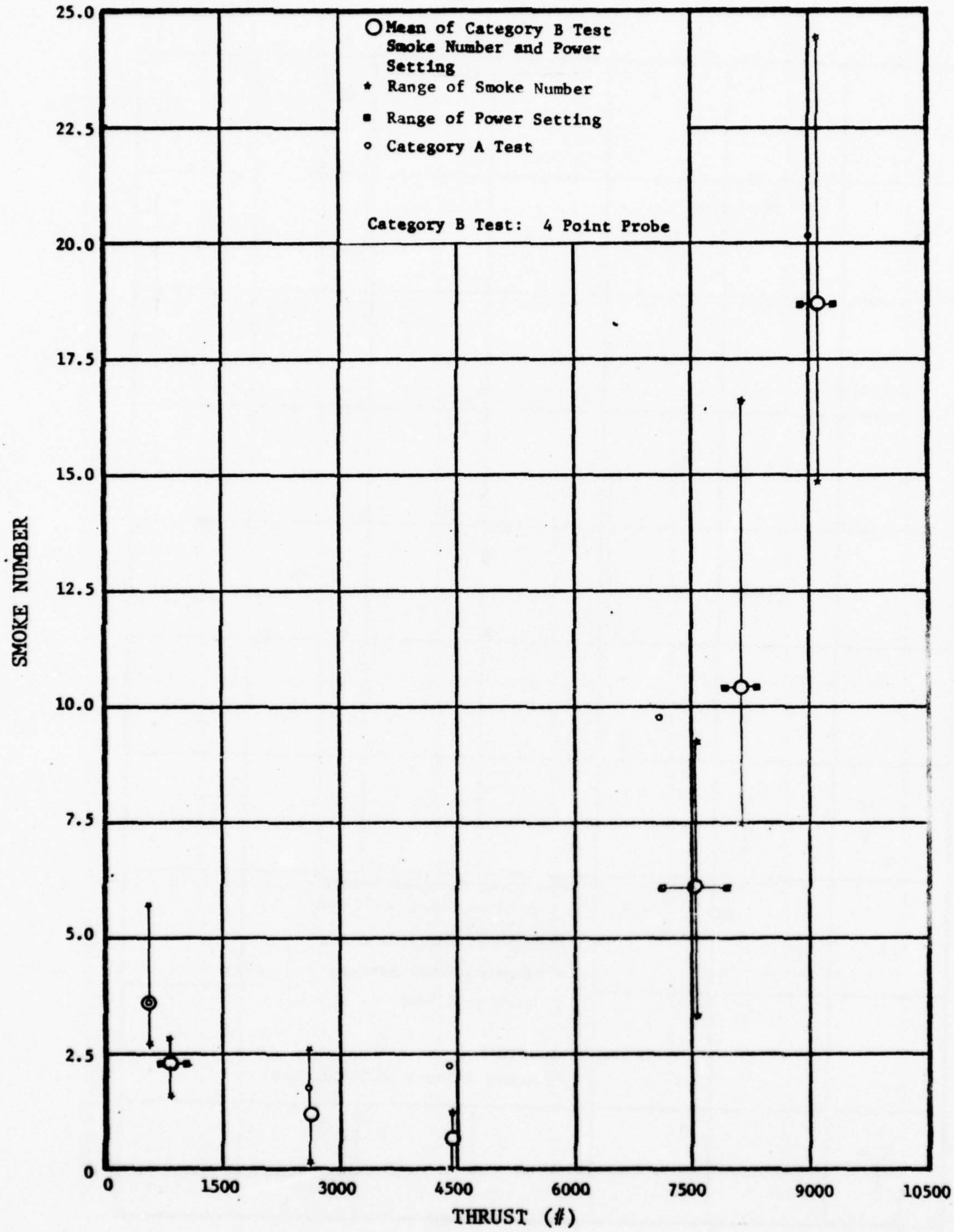


FIGURE 4-78 SMOKE NUMBER VS POWER SETTING. TF34-100 ENGINE.

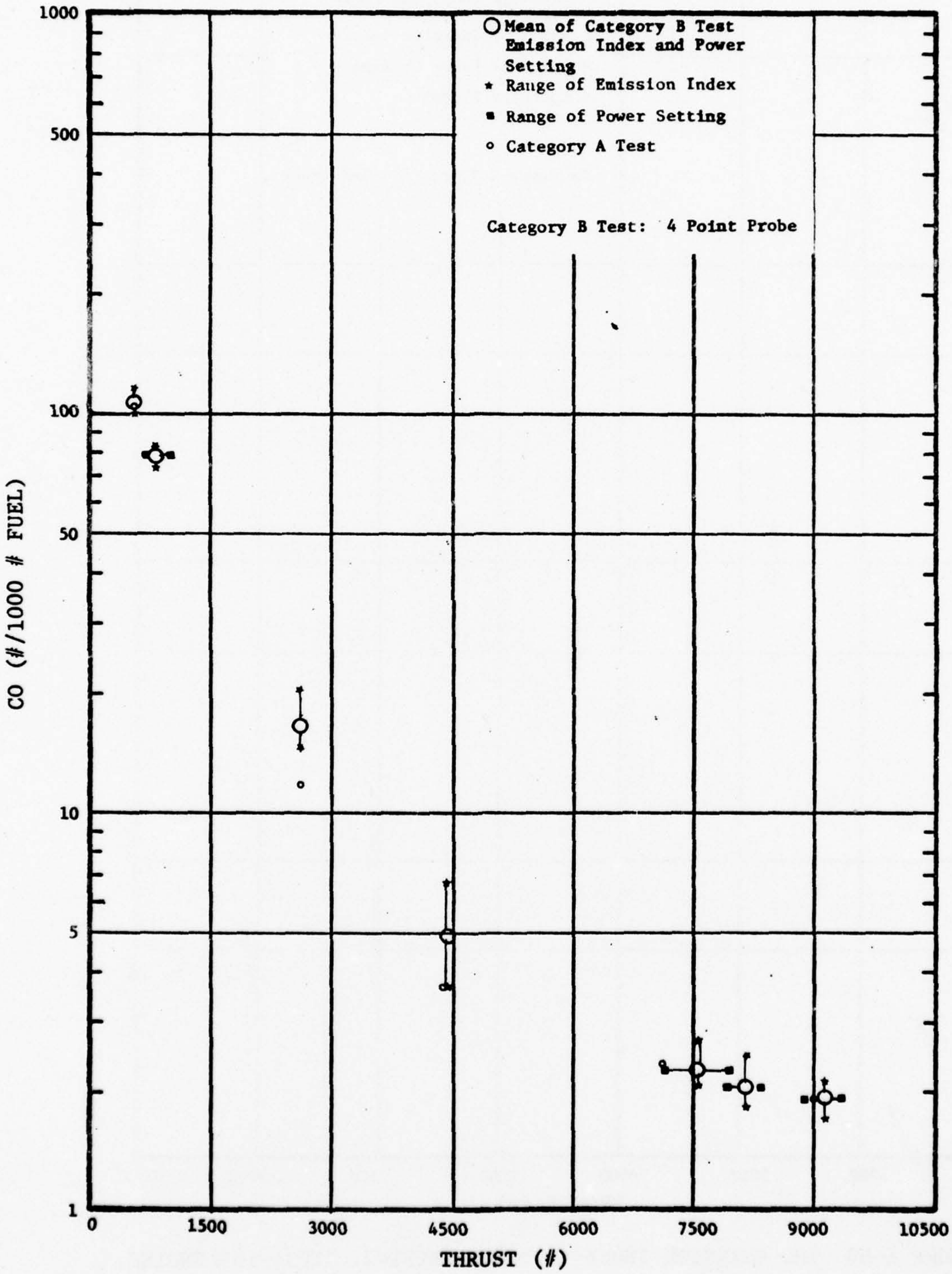


FIGURE 4-79 CO EMISSION INDEX VS POWER SETTING. TF34-100 ENGINE.

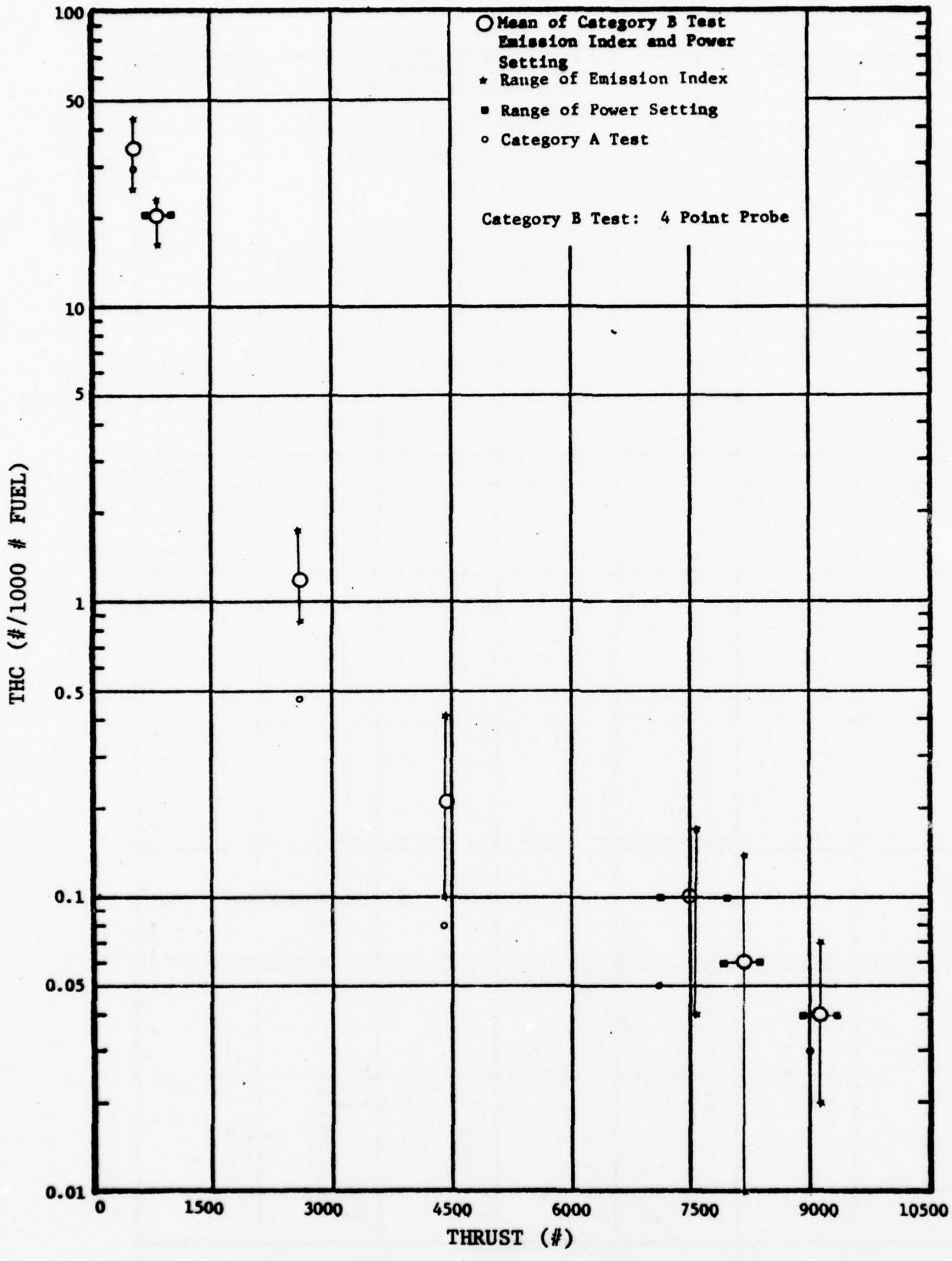


FIGURE 4-80 THC EMISSION INDEX VS POWER SETTING. TF34-100 ENGINE.

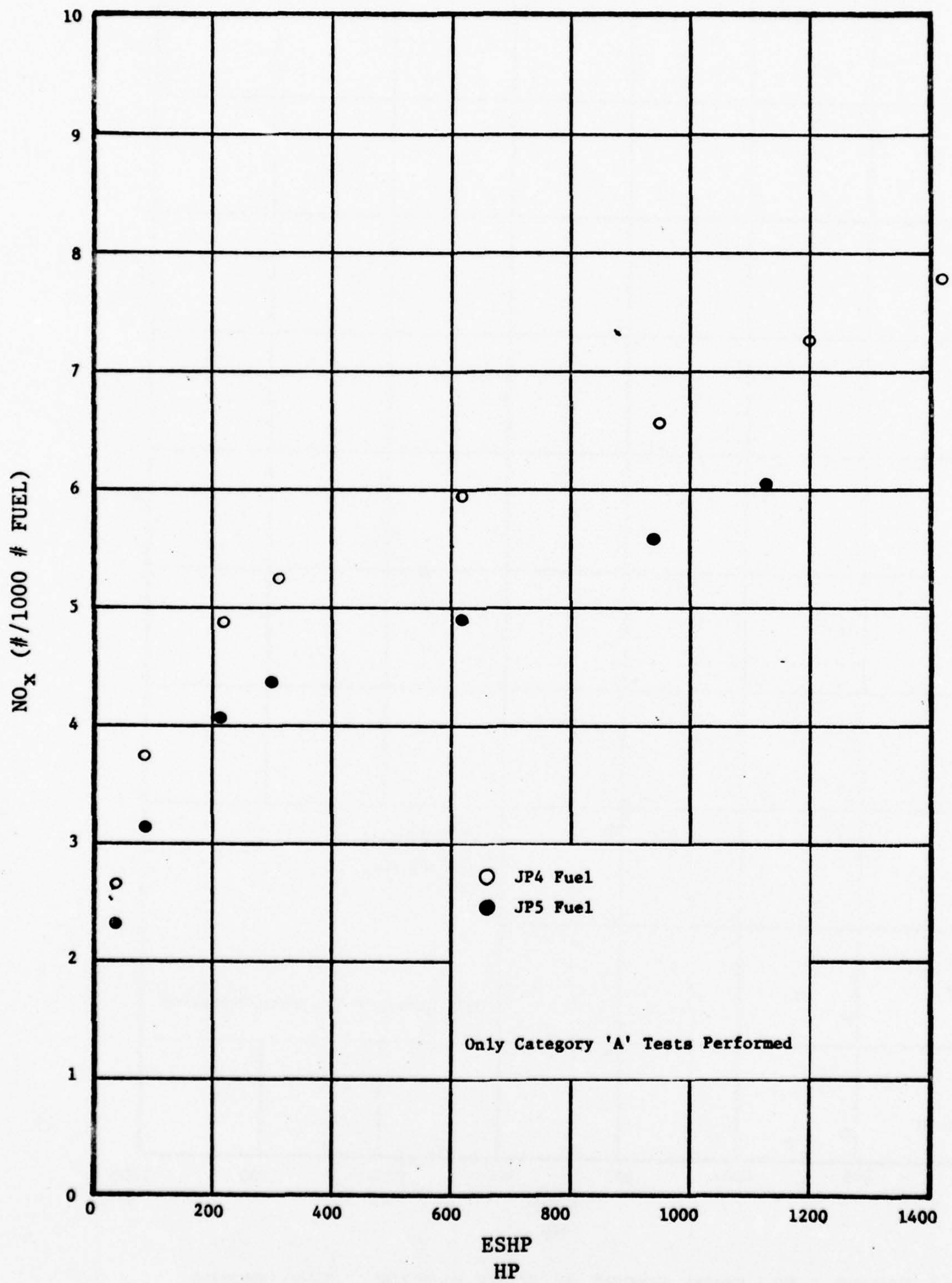


FIGURE 4-81 NO_x EMISSION INDEX VS POWER SETTING. T700 ENGINE.

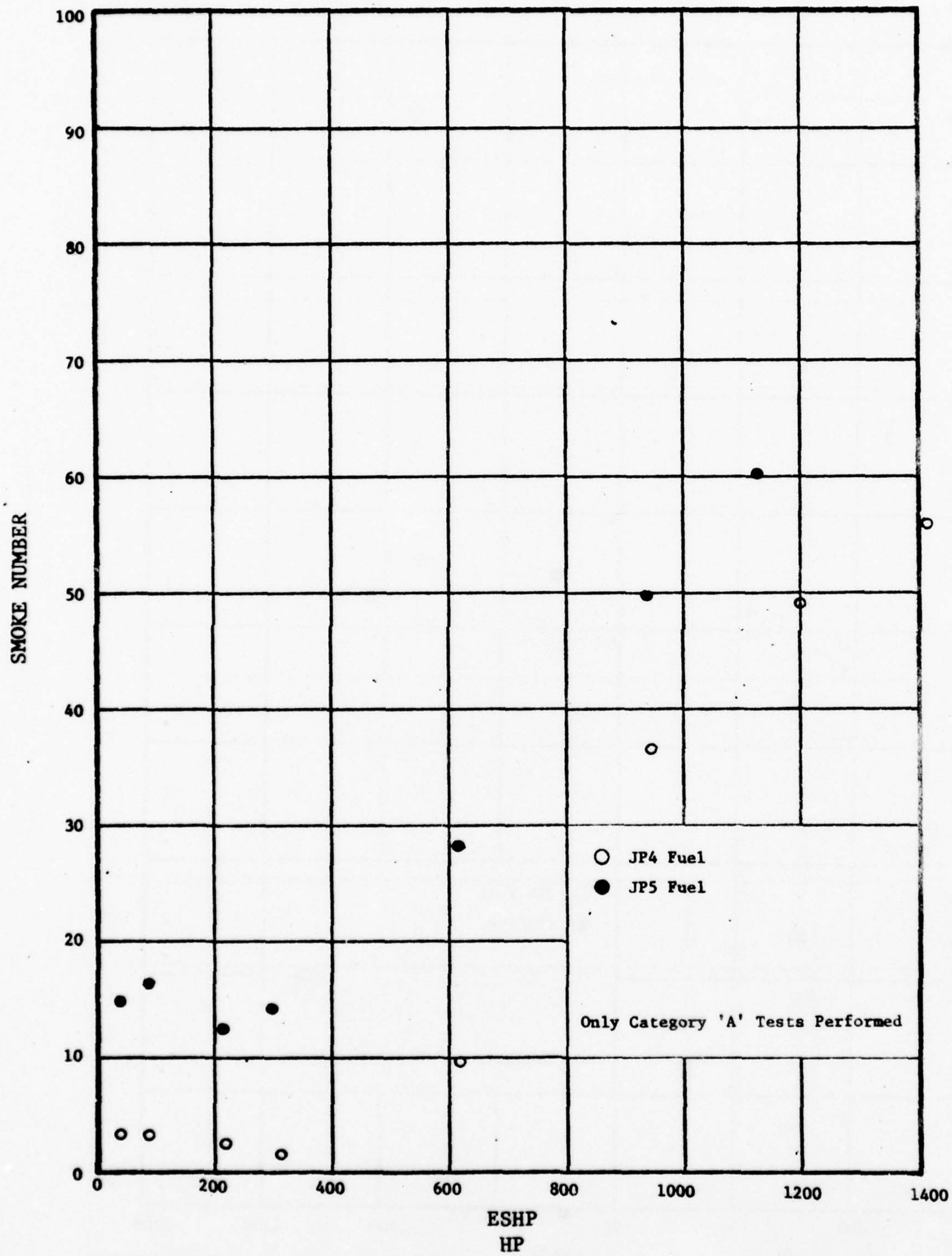


FIGURE 4-82 SMOKE NUMBER VS POWER SETTING. T700 ENGINE.

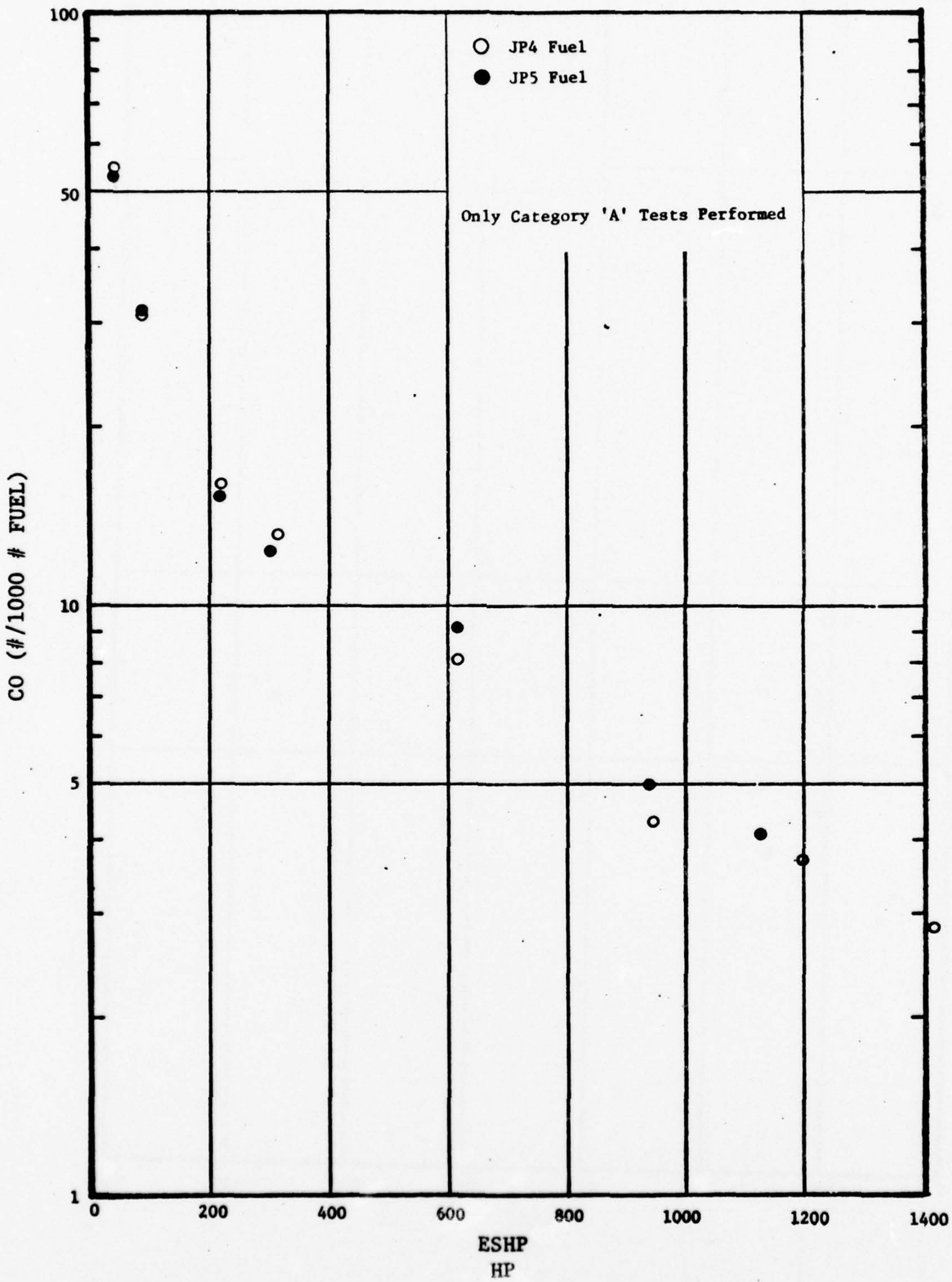


FIGURE 4-83 CO EMISSION INDEX VS POWER SETTING. T700 ENGINE.

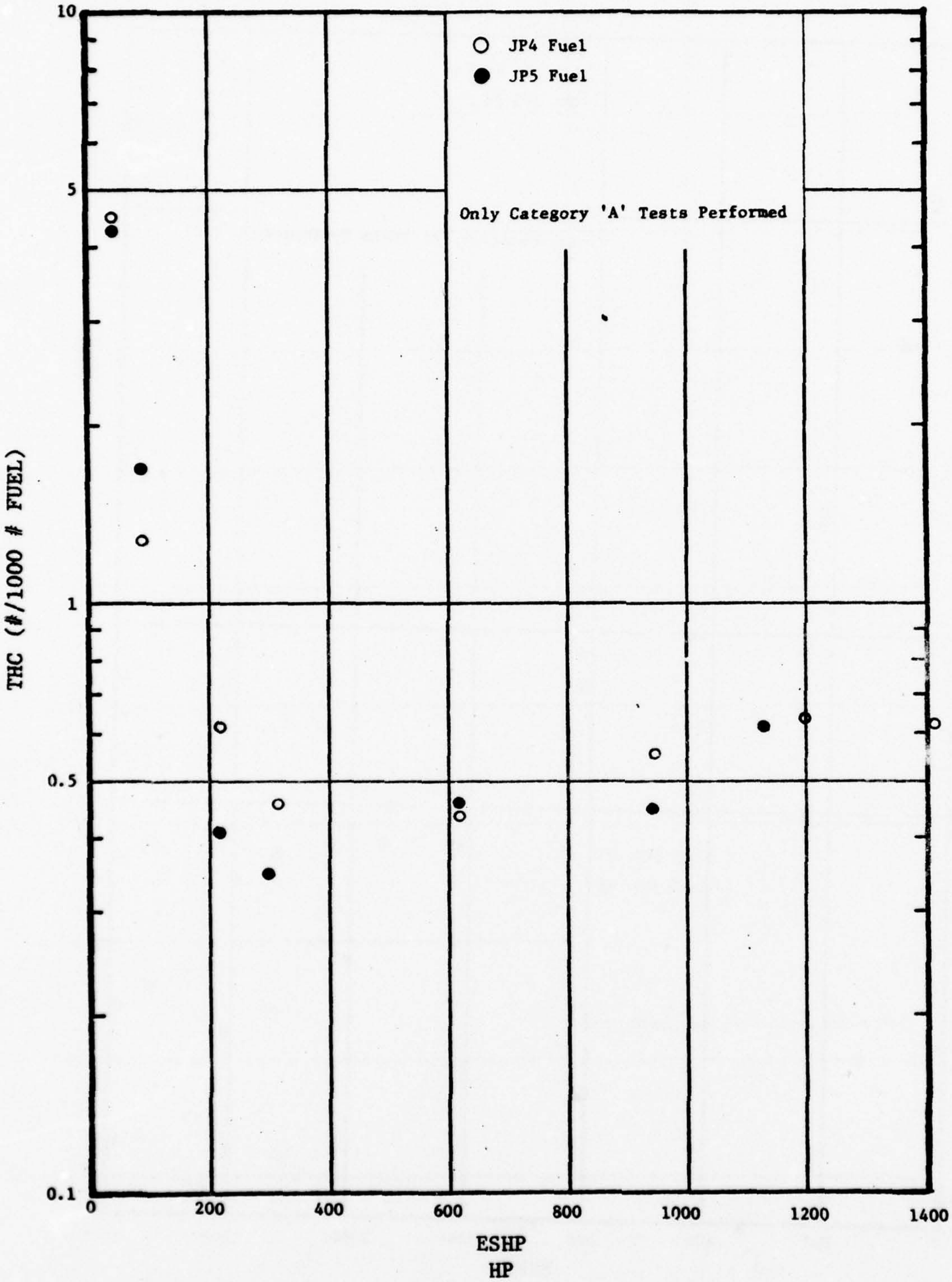


FIGURE 4-84 THC EMISSION INDEX VS POWER SETTING. T700 ENGINE.

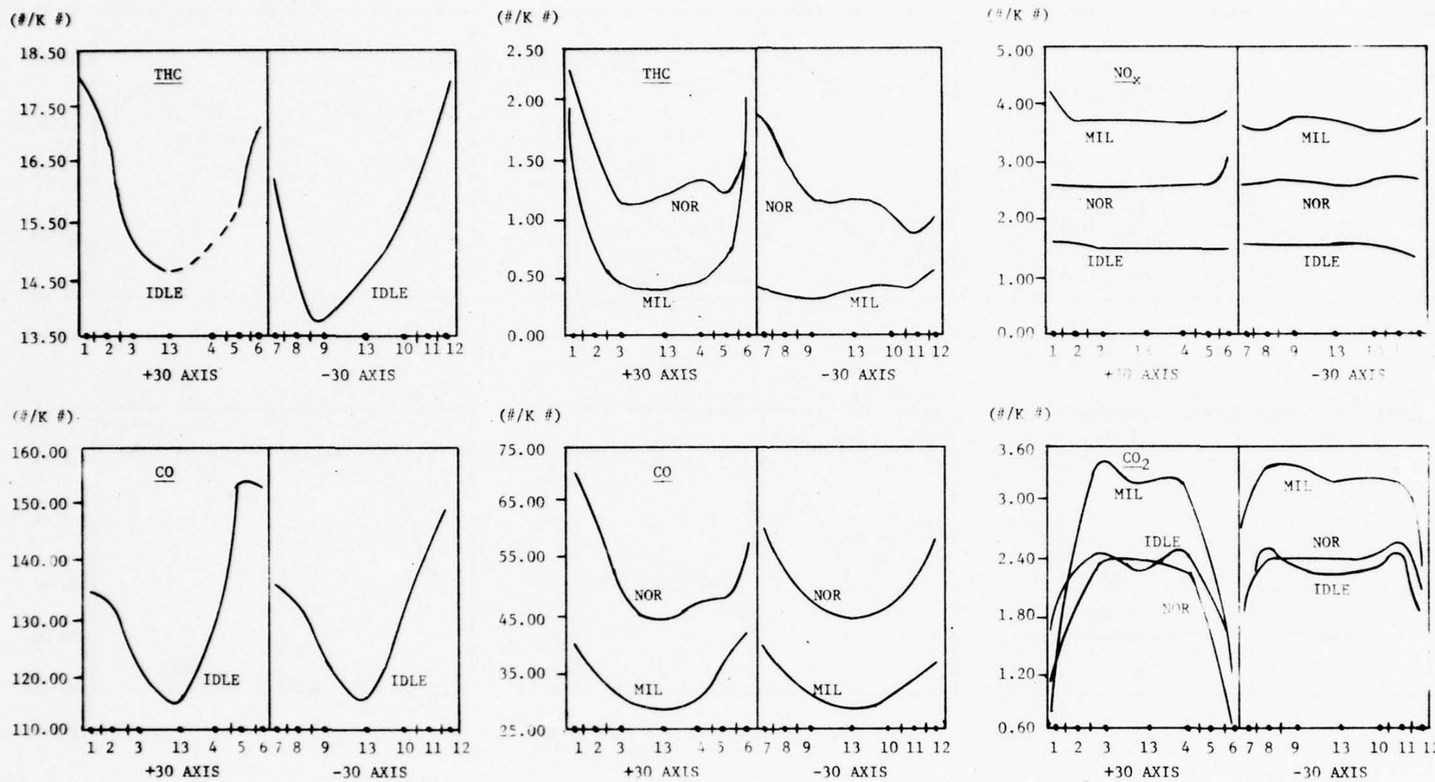


FIGURE 4-85. Emission Index and CO_2 Variation Across Exhaust Plane Engine J69-T25

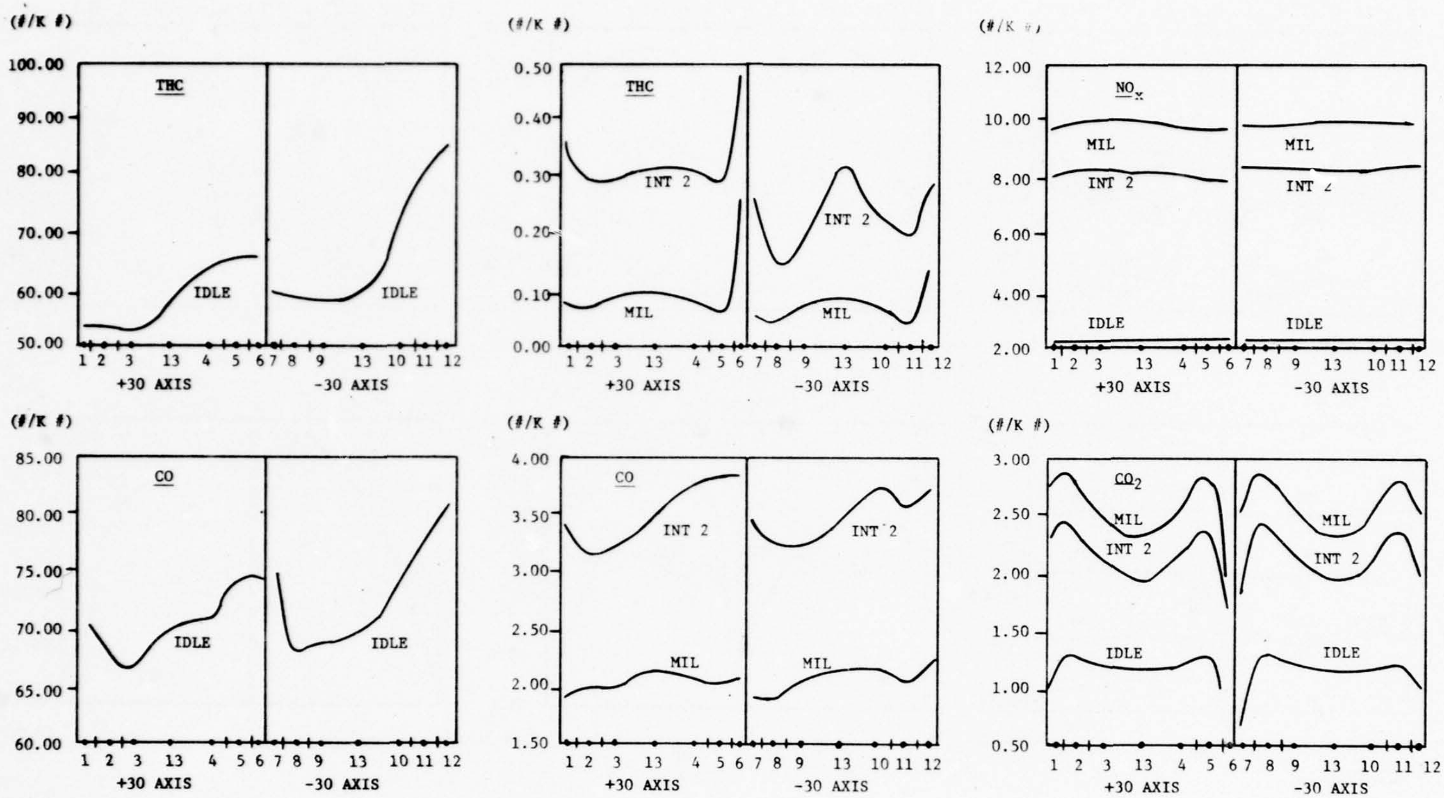


FIGURE 4-86. Emission Index and CO_2 Variation Across Exhaust Plane Engine J57-P21B

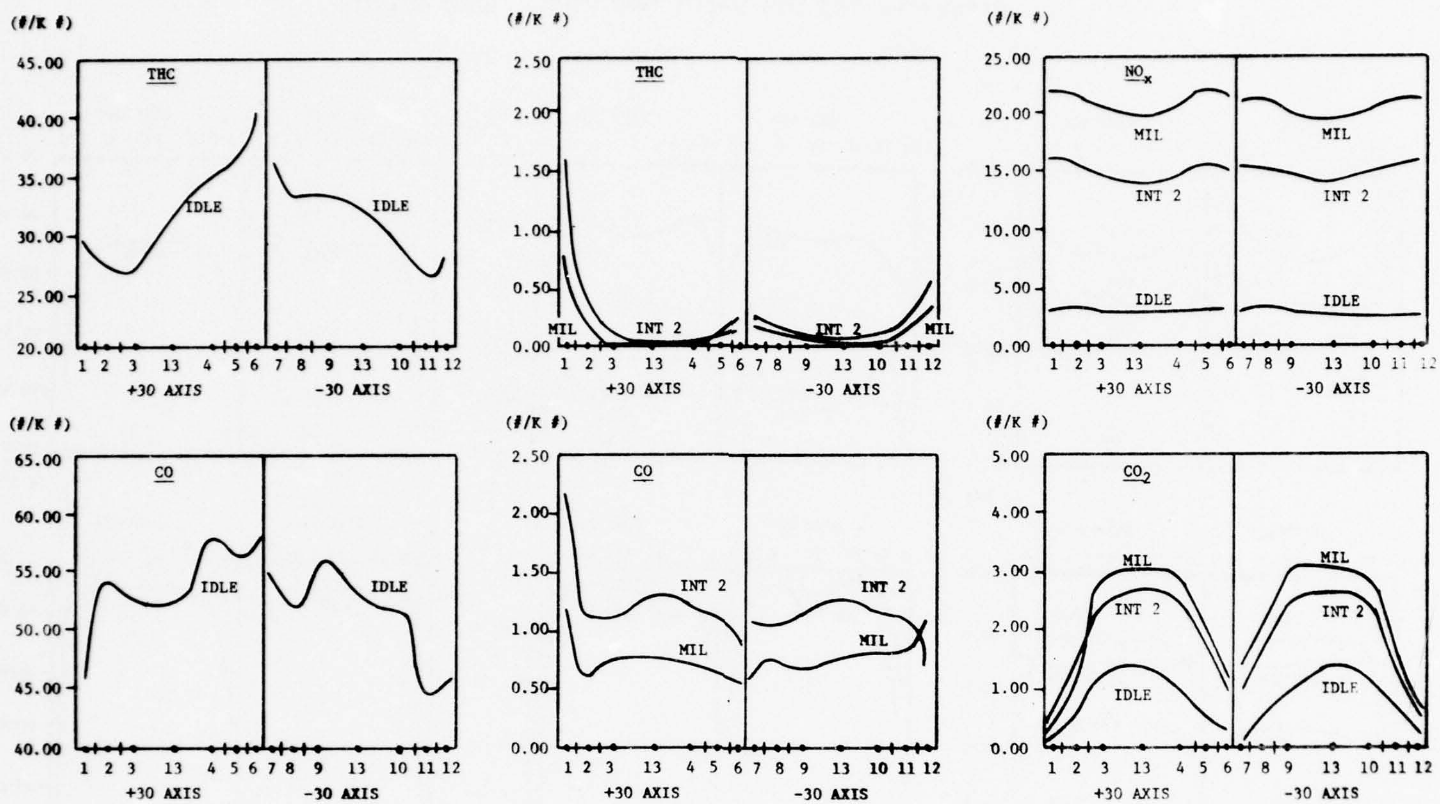


FIGURE 4-87. Emission Index and CO_2 Variation
Across Exhaust Plane
Engine TF 30-P7

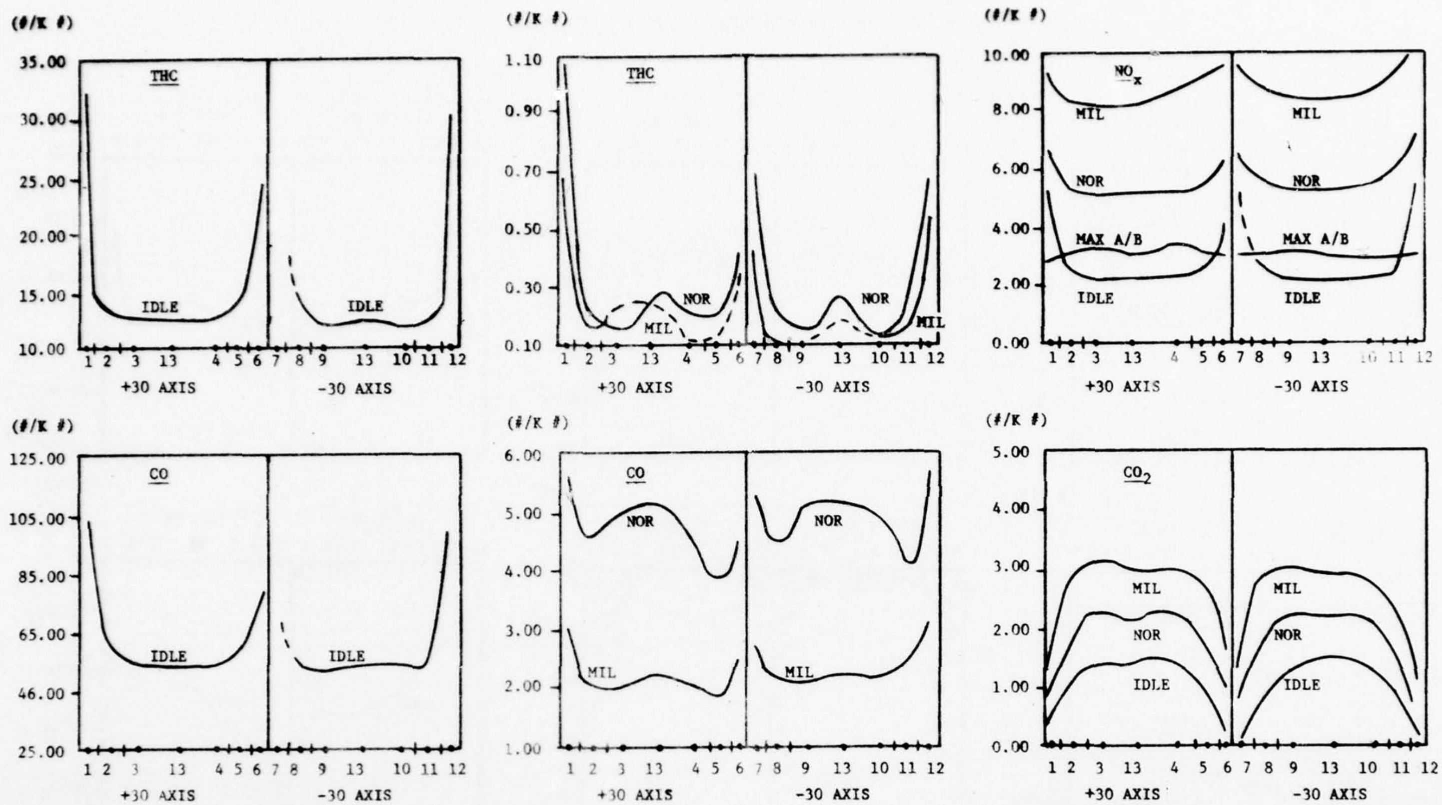


FIGURE 4-88. Emission Index and CO_2 Variation Across Exhaust Plane Engine J79-15

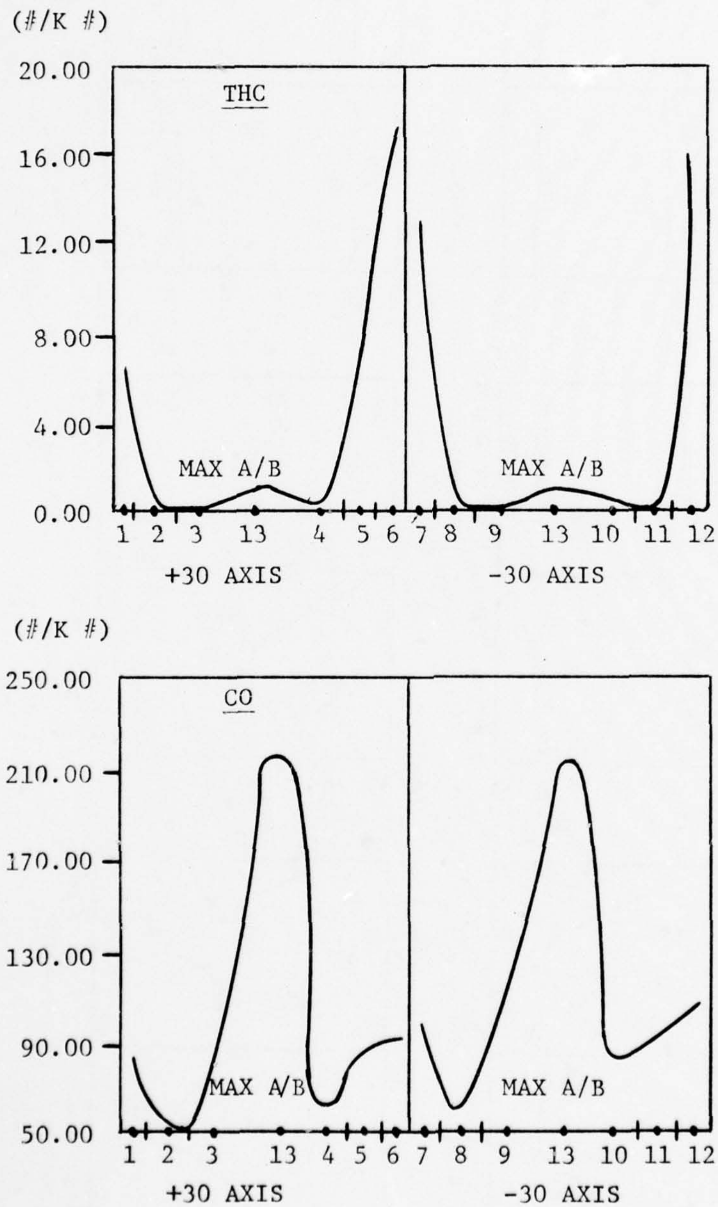


FIGURE 4-88 (CONTINUED) EMISSION INDEX AND CO_2 VARIATION ACROSS EXHAUST PLANE

ENGINE J79-15

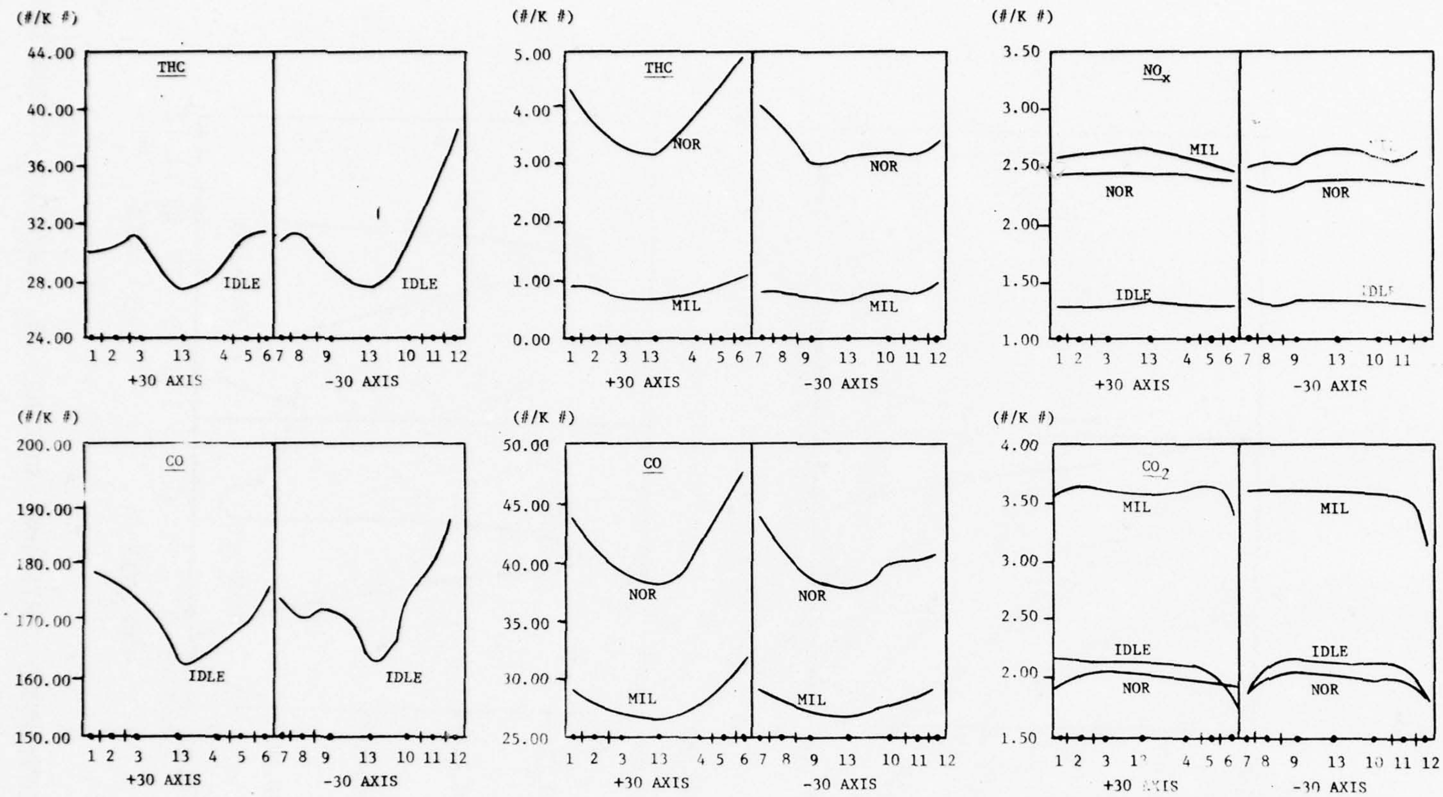


FIGURE 4-89. Emission Index and CO_2 Variation Across Exhaust Plane Engine J58-5

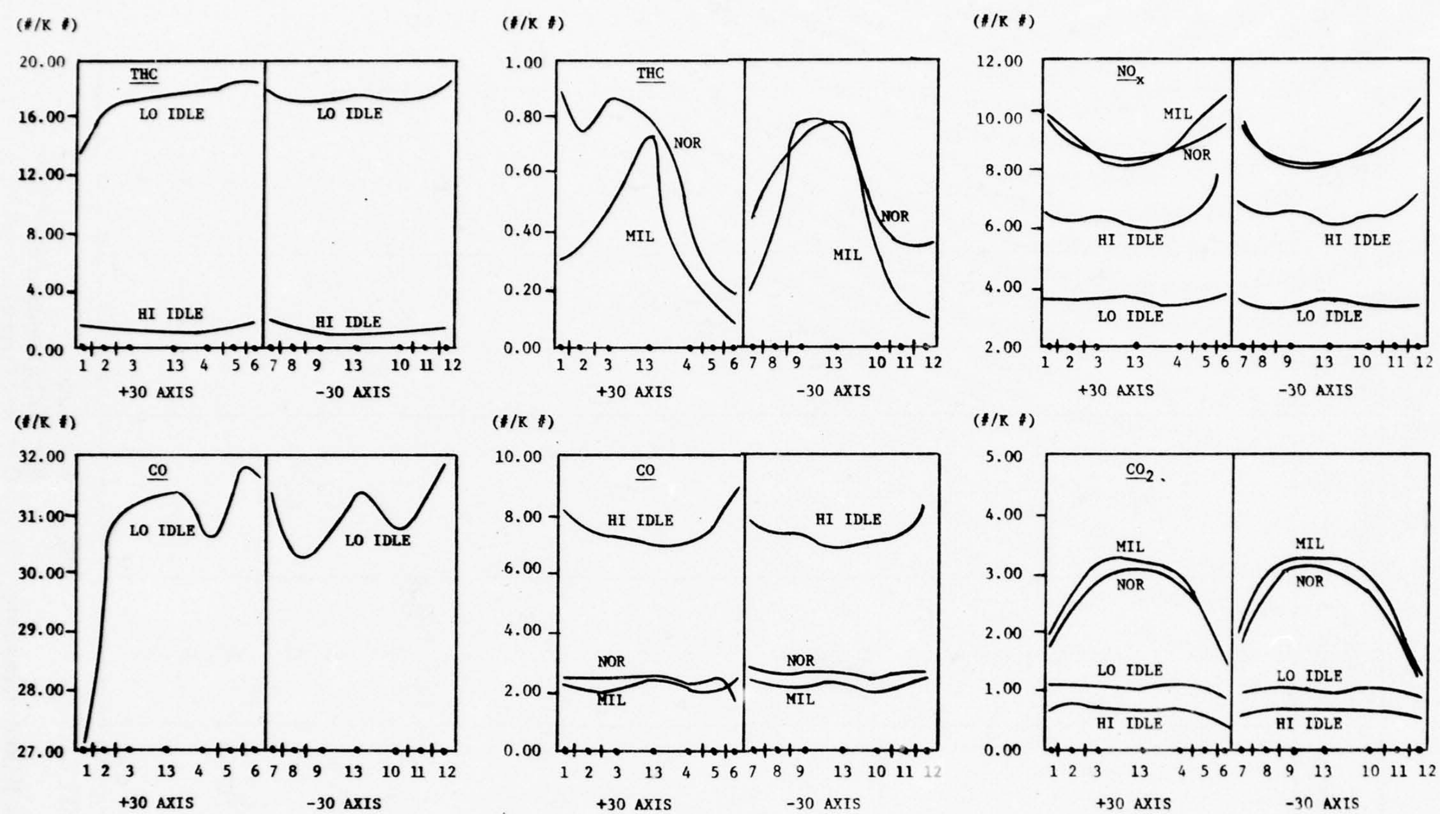


FIGURE 4-90. Emission Index and CO_2 Variation
Across Exhaust Plane
Engine T56-A7B
(Engine #5)

TABLE 4-1 CO_2 PLUME SHAPES

Engine	Type	Power Mode	Group 1	Group 2	Group 3	Group 4
J-57-19W	J	A				X
		B				X
		C				X
J57-21B J57-43	J	A				X
		B				X
		C				X
J60-P5B J60-P3	J	A				X
		B				X
		C				X
J69-T25	J	A				X
		B				X
		C				X
J75-P17	J	A				X
		B				X
		C				X
J79-15	J	A		X		
		B				X
		C				X
		Max A/B				X
J85-5	J	A	X			
	B	B	X			
		C	X			
TF30-P3 TF30-P7	TF_M	A			X	
		B			X	
		C			X	

TS = Turbo Shaft
J = Turbojet
TF_M = Turbo Fan Mixed Exhaust
TF_E = Turbo Fan External Fan

A = Idle
B = Intermediate
C = Military

TABLE 4- 1 CO_2 PLUME SHAPES
(Continued)

Engine	Type	Power Mode	Group 1	Group 2	Group 3	Group 4
TF30-P100	TF_M	A			X	
		B			X	
		C			X	
TF41-A1	TF_M	A		X		
		B		X		
		C		X		
F100-PW100	TF_M	A				X
		B				X
		C				X
TF33-P3 TF33-P7	TF_E	A				X
		B				X
		C				X
TF34	TF_E	A				X
		D				X
		F				X
T56-A7B	TS	A	X			
		C			X	
		D			X	

TS = Turbo Shaft

J = Turbojet

TF_M = Turbo Fan Mixed Exhaust

TF_E = Turbo Fan External Fan

A = Idle

B = Intermediate

C = Military

TABLE 4-2 ABBREVIATED SAMPLING METHOD (CATEGORY B TESTS) COMPARED TO THE 13-POINT METHOD (CATEGORY A TESTS)

TOTAL HYDROCARBON EMISSION INDEX (#/1000 # FUEL)

Test Type (See Note)	Idle					Intermediate					Military				
	A	B*	B Mean	B Min.	B Max.	A	B*	B Mean	B Min.	B Max.	A	B*	B Mean	B Min.	B Max.
Engine Model						Category B Test - 4 Point									
J69-T25	15.98		19.86	6.86	**35.57**	1.35		1.29	0.59	1.87	**0.53**		0.49	0.24	0.75
J85-5	31.05		29.78	23.53	**49.48**	3.74		3.33	1.53	5.32	**0.84**		0.84	0.44	1.27
J60-P5B; J60-P3	8.86		10.29	6.02	**15.21**	1.13		0.12	0.05	0.29	**0.10**		0.07	0.03	0.18
J79-15	14.39		9.99	5.68	12.43	0.26		0.24[1]	0.19	0.35	**0.19**		0.23	0.06	0.68
T56-A7B	17.21		21.20	16.40	25.31	0.55		0.54[2]	**0.11**	1.15	**0.34**		0.36	0.10	0.84
TF34-100	29.09		34.34	24.94	43.35	0.08		0.21	**0.10**	0.41	**0.05**		0.10	0.04	0.17
						Category B Test - Rake									
J57-19W	79.13	61.64	75.20	61.64	88.78	0.15	~~0.35~~	~~2.53~~	3 ~~0.35~~	~~4.94~~	0.09	~~0.44~~	~~1.44~~	3 ~~0.44~~	~~2.20~~
J57-P21B	65.22	55.29	53.44	52.14	55.29	0.27	~~0.27~~	~~0.42~~	3 ~~0.24~~	~~0.75~~	0.08	0.44	~~0.45~~	3 ~~0.35~~	~~0.57~~
J57-43; J57-F43WB	81.13	69.82	68.35	56.20	81.43	0.09	~~1.81~~	~~1.07~~	3 ~~0.58~~	~~1.81~~	0.05	~~2.21~~	~~1.48~~	3 ~~0.80~~	~~2.21~~
J75-19W			38.16	28.03	54.21			0.31	0.23	0.42			0.30	0.15	0.38
J75-P17	94.30	76.77	71.85	66.94	76.77	0.11	0.22	0.19	0.17	0.22	0.10	0.25	0.19	0.14	0.25
TF30-P3	62.11	73.20	62.87	51.43	73.20	0.19	~~10.87~~	~~9.20~~	3 ~~4.06~~	~~10.87~~	0.12	~~17.53~~	~~9.94~~	3 ~~5.74~~	~~17.53~~
TF30-P7	30.94	29.72	29.74	24.87	**34**.68	0.15	~~8.23~~	~~11.30~~	3 ~~8.23~~	~~14.55~~	0.09	~~10.06~~	~~13.74~~	3 ~~8.51~~	~~22.66~~
TF30-P100	20.22	17.47	18.16	16.30	19.51	0.12	~~5.94~~	~~2.94~~	3 ~~1.05~~	~~5.94~~	0.09	~~5.60~~	~~3.29~~	3 ~~1.09~~	~~5.60~~
TF33-P3	108.9	117.5	105.5	77.54	128.3	0.80	0.71	0.58	0.41	0.**71**	0.75	0.63	0.39	0.26	0.63
TF33-P7	86.98	62.05	67.15	56.86	83.08	0.10	~~0.26~~	~~0.42~~	3 ~~0.26~~	~~0.54~~	0.03	~~0.19~~	~~0.30~~	3 ~~0.19~~	~~0.37~~
TF41-A1	91.80	88.12	92.61	75.33	107.4	0.36	~~1.37~~	~~0.97~~	3 ~~0.26~~	~~1.37~~	0.15	~~6.25~~	~~3.72~~	3 ~~0.34~~	~~6.25~~
F100-PW100	2.84	2.03	3.68	2.03	6.10	0.08	0.08	0.17	0.01	0.37	0.19	0.00	0.08	0.00	0.20

NOTE: Test Types
A - Category 'A' test sampling 13 points on two axes 60° apart.
B - Category 'B' test sampling 4 points on one axis or sampling with rake probe.
B*- Category 'B' test done on the same engine as the 'A' test.

1. One outlier removed (1.51)
2. Glycol leak in probe 4 tests deleted
3. Glycol leak in probe. B tests deleted

TABLE 4-3 ABBREVIATED SAMPLING METHOD (CATEGORY B TESTS) COMPARED TO THE 13-POINT METHOD (CATEGORY A TESTS)

CARBON MONOXIDE EMISSION INDEX (#/1000 # FUEL)

Test Type (See Note)	Idle					Intermediate					Military				
	A	B*	B			A	B*	B			A	B*	B		
			Mean	Min.	Max.			Mean	Min.	Max.			Mean	Min.	Max.
Engine Model	Category B Test - 4 Point														
J69-T25	134.5		126.4	103.8	161.5	52.64		48.72	36.50	56.27	34.24		31.02	28.25	33.39
J85-5	172.9		180.3	167.0	204.4	41.30		43.57	39.72	48.58	28.07		29.47	27.00	33.48
J60-P5B; J60-P3	68.13		71.60	63.24	82.02	5.85		5.69	5.23	6.63	4.13		3.81	3.58	4.46
J79-15	58.28		56.43	53.37	65.31	4.68		4.49	3.98	5.37	2.16		2.30	1.90	2.77
T56-A7B	31.98		31.72	30.47	32.72	2.53		2.19	1.73	3.00	2.19		1.95	1.58	2.37
TF34-100	104.4		106.6	101.0	116.0	3.62		4.89	3.64	6.67	2.33		2.26	2.07	2.70
	Category B Test - Rake														
J57-19W	80.82	73.05	76.44	73.05	81.14	2.38	2.66	2.45	2.23	2.66	1.87	1.88	1.85	1.79	1.88
J57-P21B	72.67	69.02	70.03	69.02	71.75	3.49	3.33	2.73	2.38	3.33	2.02	2.19	1.91	1.57	2.19
J57-43; J57-F43WB	86.03	75.81	72.35	69.08	75.81	2.00	1.92	2.05	1.92	2.21	1.41	1.51	1.59	1.51	1.66
J75-19W			62.62	54.05	67.66			1.86	1.66	2.08			1.47	1.29	1.69
J75-P17	86.39	89.75	86.01	82.27	89.75	1.88	1.83	1.83	1.83	1.84	1.29	1.38	1.40	1.33	1.42
TF30-P3	71.54	78.86	72.77	65.80	78.86	2.05	3.09	2.53	2.02	3.09	1.25	2.11	1.52	1.15	2.11
TF30-P7	53.36	57.64	52.58	43.59	57.64	1.11	1.26	1.24	1.15	1.30	0.72	0.78	0.91	0.76	1.18
TF30-P100	48.91	49.82	48.02	44.77	51.86	0.65	1.10	0.80	0.61	1.10	0.72	1.00	0.77	0.55	1.00
TF33-P3	83.93	85.82	84.02	79.52	88.46	2.93	2.35	2.28	2.01	2.73	2.24	1.87	1.66	1.54	1.87
TF33-P7	96.44	87.24	89.67	87.24	93.86	1.29	1.16	1.24	0.97	1.47	0.79	0.78	0.80	0.68	0.94
TF41-A1	118.2	118.9	119.5	115.5	122.5	3.75	3.66	3.57	2.94	4.07	1.87	1.94	1.81	1.54	1.94
F100-PW100	24.04	21.77	24.39	19.51	30.30	1.77	1.03	1.05	0.92	1.17	0.89	0.91	0.80	0.63	0.94

NOTE: Test Types

A - Category 'A' test sampling 13 points on two axes 60^{o} apart.

B - Category 'B' test sampling 4 points on one axis or sampling with rake probe.

B*- Category 'B' test done on the same engine as the 'A' test.

TABLE 4-4 ABBREVIATED SAMPLING METHOD (CATEGORY B TESTS) COMPARED TO THE 13-POINT METHOD (CATEGORY A TEST)

NITROGEN OXIDES EMISSION INDEX (#/1000 # FUEL)

Test Type (See Note)	Idle					Intermediate					Military				
	A	B*	B Mean	B Min.	B Max.	A	B*	B Mean	B Min.	B Max.	A	B*	B Mean	B Min.	B Max.
Engine Model	Category B Test - 4 Point														
J69-T25	1.52		1.53	1.27	1.80	2.61		2.68	1.67	3.31	3.60		3.60	2.66	4.15
J85-5	1.29		1.26	1.17	1.39	2.35		2.32	1.96	3.14	2.53		2.70	2.38	3.71
J60-P5B; J60-P3	1.48		1.49	1.06	1.68	3.90		4.10	3.68	4.34	4.50		4.76	4.20	5.05
J79-15	2.50		2.46	2.41	2.54	5.47		5.75	4.70	6.65	8.73		8.98	7.67	11.30
T56-A7B	3.48		3.90	3.56	4.47	9.27		9.12	8.18	9.91	9.38		9.22	8.43	10.07
TF34-100	2.01		2.08	1.99	2.22	7.24		7.65	7.16	8.42	9.75		10.34	9.77	11.34
	Category B Test - Rake														
J57-19W	2.27	2.14	2.17	2.12	2.24	9.80	8.32	8.76	8.32	9.11	10.80	9.94	10.26	9.94	10.80
J57-P21B	2.41	2.19	2.23	2.19	2.26	8.26	7.73	8.32	7.73	8.72	9.78	9.07	9.94	9.07	10.41
J57-43; J57-F43WB	2.22	1.96	2.14	1.96	2.29	10.32	9.42	9.45	8.86	10.60	11.26	10.68	10.75	10.03	11.89
J75-19W			2.55	2.48	2.59			8.95	8.55	9.18			10.48	10.16	10.83
J75-P17	2.31	2.36	2.30	2.25	2.36	10.61	9.77	9.49	9.22	9.77	12.63	11.34	11.15	10.96	11.34
TF30-P3	2.42	1.88	2.15	1.88	2.46	11.63	10.30	10.44	9.84	11.19	14.00	12.81	13.14	12.31	14.30
TF30-P7	3.19	2.72	2.77	2.56	3.04	15.26	13.11	13.37	13.11	13.76	20.95	18.02	17.82	17.00	18.45
TF30-P100	2.98	2.64	2.74	2.64	2.87	20.83	19.78	19.89	18.39	21.61	29.64	27.26	26.49	23.81	27.62
TF33-P3	2.20	1.95	1.84	1.68	1.95	8.98	7.92	8.05	7.52	8.51	10.65	8.99	9.47	8.99	9.92
TF33-P7	1.69	1.79	1.82	1.69	1.96	9.63	8.79	9.13	8.25	10.14	11.85	10.98	11.22	9.62	12.48
TF41-A1	1.54	1.45	1.41	1.31	1.50	12.74	12.64	12.21	11.54	13.57	21.55	21.97	21.31	11.51	22.49
F100-PW100	3.33	3.25	3.35	3.21	3.58	9.22	11.25	11.22	10.05	12.21	26.69	23.86	26.66	23.86	30.48

NOTE: Test Types

A - Category 'A' test sampling 13 points on two axes 60^{o} apart.

B - Category 'B' test sampling 4 points on one axis or sampling with rake probe.

B* - Category 'B' test done on the same engine as the 'A' test.

TABLE 4-5 ABBREVIATED SAMPLING METHOD (CATEGORY B TESTS) COMPARED TO THE 13-POINT METHOD (CATEGORY A TESTS)

SMOKE NUMBER

Test Type (See Note)	Idle					Intermediate					Military				
	A	B*	B Mean	B Min.	B Max.	A	B*	B Mean	B Min.	B Max.	A	B*	B Mean	B Min.	B Max.
Engine Model	Category B Test - 4 Point														
J69-T25	32.55		39.40	24.48	48.05	1.67		2.02	0.00	7.97	3.24		2.67	0.00	11.20
J85-5	0.00		0.46	0.00	3.10	0.00		1.62	0.00	5.58	3.58		2.79	0.50	7.37
J60-P5B; J60-P3	0.25		1.93	0.67	4.00	17.25		17.04	11.75	22.00	17.75		17.41	10.50	22.50
J79-15	21.42		21.22	15.65	23.82	57.62		59.63	55.75	62.75	58.42		60.71	59.88	61.75
T56-A7B	23.58		23.18	13.75	34.00	36.42		36.14	28.50	40.13	37.25		37.66	28.25	44.63
TF34-100	3.67		3.63	2.75	5.75	2.25		0.68	0.00	1.25	9.79		6.13	3.38	9.25
	Category B Test - Rake														
J57-19W	7.67	10.50	10.90	10.50	11.20	56.92	58.00	59.90	58.00	61.20	55.83	59.00	60.73	59.00	61.70
J57-P21B	8.75	11.00	12.17	11.00	14.00	59.92	62.00	60.50	58.00	62.00	61.63	62.50	61.00	58.00	62.50
J57-43; J57-F43WB	7.58	6.50	8.97	6.50	10.40	55.00	55.50	58.00	55.50	62.50	55.75	57.50	59.27	57.50	62.50
J75-19W			10.67	10.00	11.00			51.00	50.00	52.00			51.50	50.00	53.50
J75-P17	10.50	15.00	14.25	13.50	15.00	53.25	60.00	53.50	47.00	60.00	53.58	50.50	49.75	49.00	50.50
TF30-P3	0.25	1.60	3.03	1.60	4.00	28.00	35.70	36.73	35.70	37.50	29.21	33.70	33.80	30.00	37.70
TF30-P7	1.03	2.70	4.57	2.70	8.00	29.17	33.20	34.40	32.50	37.50	27.63	30.50	33.17	30.50	34.50
TF30-P100	1.08	5.00	4.38	3.50	5.00	26.00	31.70	31.60	28.00	35.50	24.50	28.50	27.42	25.00	31.00
TF33-P3	10.50	18.50	15.00	10.50	18.50	54.67	61.50	56.88	51.00	61.50	54.50	62.00	53.88	51.00	62.00
TF33-P7	6.97	6.00	9.50	6.00	15.00	50.93	49.50	47.63	40.00	52.00	47.98	51.00	47.00	40.00	51.00
TF41-A1	7.50	19.00	13.00	9.50	19.00	27.92	44.00	40.20	33.00	44.00	34.00	48.50	47.70	45.00	51.00
F100-PW100	4.80	11.50	12.17	4.00	20.20	23.92	32.00	31.92	28.20	35.50	26.84	35.00	34.50	32.50	35.70

NOTE: Test Types

A - Category 'A' test sampling 13 points on two axes 60° apart.

B - Category 'B' test sampling 4 points on one axis or sampling with rake probe.

B*- Category 'B' test done on the same engine as the 'A' test.

5.0 EMISSION FACTORS FOR AIR FORCE GAS TURBINE ENGINES

Utilizing the relative merits of the Category A and Category B test methods discussed earlier in this report, the two sets of data obtained for each engine type measured were combined into a single set of emission factors. These "Best Estimate" emission factors names a value of pollutant emission rate at each of three power settings: Idle, Intermediate and Military thus fulfilling the primary goal of this project.

The category B data obtained on this project was indicative of the engine-to-engine variability, and the mean value of the Category B emission rates for each engine is therefore of value statistically. The Category A tests on the other hand were considered more accurate because of the greater number of sampling points involved.

A technique was agreed to by the contract officer for combining the Category A and the Category B data. This technique was as follows:

1. It was determined if the Category A data was within $\pm 2\sigma$ of the mean of the B data.
2. If the Category A data was within $\pm 2\sigma$ of the B data, then the two data were pooled.
3. If the Category A data was not within $\pm 2\sigma$ of the B data, then a judgement was made as to which data was more correct.

The pooled data were combined by scoring each Category A test as being worth four times as much as a Category B test. The results produce a table of "Best Estimates Emission Factors" which is presented as Table 5-1.

The documentation of the determinations of the best estimate is presented as Tables 5-2 through 5-20. In each of these tables the average of the Category A data points, the Category B data mean value and the number of observations made in each category are listed for each power setting. The standard deviation of the B data is also included. The data were then treated according to the technique listed above. Footnotes at the bottom of the table for each engine type list the considerations used in each case where the Category A data was not within $\pm 2\sigma$ of the Category B mean.

TABLE 5-1 BEST ESTIMATE EMISSION FACTORS

	Idle					Intermediate					Military				
	lbs/K lbs Fuel				lbs/hr	lbs/K lbs Fuel				lbs/hr	lbs/K lbs Fuel				lbs/hr
Engine	THC	CO	NO_x	S/N	Fuel Flow	THC	CO	NO_x	S/N	Fuel Flow	THC	CO	NO_x	S/N	Fuel Flow
J69-T25	19	129	1.5	37	220	1.3	50	2.7	1.9	528	0.5	32	3.6	2.8	1095
J85-5	30	178	1.3	0.3	453	3.5	43	2.3	1.1	1145	0.8	29	2.6	3.0	2630
J60-P5B; P3	9.2	70	1.5	1.5	420	0.2	5.8	4.0	18	1320	0.1	4.0	4.6	19	2125
J79-15	12	57	2.5	21	1131	0.3	4.6	5.6	59	5364	0.2	2.2	8.9	60	8921
T56-A7B	21	32	3.9	23	570	0.5	2.4	9.2	36	1851	0.4	2.1	9.3	37	1967
TF34-100	32	106	2.0	3.6	388	0.2	4.3	7.5	1.4	1472	0.1	2.3	10	7.8	2575
J57-19W	77	79	2.2	9	942	0.2	2.4	9.5	58	6373	0.1	1.9	11	58	7447
J57-P21B	60	72	2.3	10	1051	0.3	3.2	8.3	60	6442	0.1	2.0	9.8	61	7752
J57-43,43B	75	78	2.2	8.3	979	0.1	2.3	9.9	57	6653	0.1	1.5	11	58	7714
J75-19W	38	62	2.6	11	1584	0.3	1.9	9.0	51	11932	0.3	1.5	10	52	13604
J75-17	72	86	2.3	12	1525	0.1	1.9	10	53	10458	0.1	1.3	12	52	12441
TF30-P3	62	72	2.3	0.3	847	0.2	2.3	11	28	4933	0.1	1.4	14	29	6176
TF30-P7	30	53	3.0	1.0	920	0.2	1.2	14	29	5417	0.1	0.8	20	28	6904
TF30-P100	19	48	2.9	1.0	1019	0.1	0.7	20	26	7184	0.1	0.7	28	24	9114
TF33-P3	107	84	1.8	13	895	0.7	2.3	8.5	56	6276	0.6	1.7	10	56	7441
TF33-P7	77	93	1.8	8.2	1068	0.1	1.3	9.4	49	7290	.03	0.8	12	47	8757
TF41-A1	92	119	1.5	11	1006	0.4	3.7	12	35	5821	0.2	1.8	21	42	8403
F100-PW100	3.2	24	3.3	5.7	1400	0.1	1.6	9.8	28	5270	0.1	0.9	27	31	10380
TF39	23	67	3.0	1.4	1134	0.2	0.7	28	5.6	12025	0.2	0.7	28	5.0	12688

TABLE 5-2 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - J69-T25

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
	IDLE	15.98	1	19.86	10	10.4	19
THC	INT	1.35	1	1.29	10	0.50	1.3
	MIL	0.53	1	0.49	10	0.16	0.5
	IDLE	134.5	1	126.4	10	22.0	129
CO	INT	52.64	1	48.7	10	5.65	50
	MIL	34.24	1	31.0	10	1.60	32
	IDLE	1.52	1	1.53	9	0.58	1.5
NO_x	INT	2.61	1	2.68	9	0.56	2.7
	MIL	3.60	1	3.60	9	0.47	3.6
	IDLE	32.55	1	39.4	10	8.21	37
SMOKE	INT	1.67	1	2.02	10	2.50	1.9
	MIL	3.24	1	2.67	10	3.59	2.8

TABLE 5-3 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - J85-5

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
	IDLE	31.05	1	29.78	9	8.15	30
THC	INT	3.74	1	3.33	9	1.22	3.5
	MIL	0.84	1	0.84	9	0.27	0.8
	IDLE	172.9	1	180.3	9	11.0	178
CO	INT	41.30	1	43.57	9	2.77	43
	MIL	28.07	1	29.47	9	2.26	29
	IDLE	1.29	1	1.26	9	.07	1.3
NO_x	INT	2.35	1	2.32	9	.35	2.3
	MIL	2.53	1	2.70	9	.42	2.6
	IDLE	0.00	1	0.46	9	1.05	0.3
SMOKE	INT	0.00	1	1.62	9	1.90	1.1
	MIL	3.58	1	2.79	9	1.96	3.0

TABLE 5-4 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - J60-P3, P5B

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
	IDLE	8.11	2	10.29	8	3.90	9.2
THC	INT	0.19	2	0.12	8	.078	0.2
	MIL	0.16	2	0.07	8	.058	0.1
	IDLE	68.13	2	71.60	8	6.88	70
CO	INT	5.85	2	5.69	8	0.45	5.8
	MIL	4.13	2	3.81	8	0.31	4.0
	IDLE	1.48	2	1.49	8	0.20	1.5
NO_x	INT	3.90	2	4.10	8	0.22	4.0
	MIL	4.50	2	4.76	8	0.30	4.6
	IDLE	1.04	2	1.93	8	1.09	1.5
SMOKE	INT	18.71	2	17.04	8	3.80	18
	MIL	20.13	2	17.41	8	4.41	19

TABLE 5-5 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - J79-15

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
	IDLE	14.39	1	9.99	5	2.77	12
THC	INT	0.26	1	0.25 (1)	4	0.07	0.3
	MIL	0.19	1	0.23	5	.26	0.2
	IDLE	58.28	1	56.43	5	5.05	57
CO	INT	4.68	1	4.49	5	0.59	4.6
	MIL	2.16	1	2.30	5	0.40	2.2
	IDLE	2.50	1	2.46	3	.07	2.5
NO_x	INT	5.47	1	5.75	5	.80	5.6
	MIL	8.73	1	8.98	5	1.36	8.9
	IDLE	21.42	1	21.22	5	3.61	21
SMOKE	INT	57.62	1	59.63	5	3.29	59
	MIL	58.42	1	60.71	5	0.81	60

NOTES: (1) One outlier removed (glycol leak).

TABLE 5-6 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - T56-A7B

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	Best ESTIMATE
	IDLE	20.3	2	21.2	7	3.5	21.0
THC	INT	0.55	1	0.54 (1)	4	.47	0.5
	MIL	0.34	1	0.36 (1)	4	.32	1.4
	IDLE	31.98	2	31.72	7	0.76	32
CO	INT	2.53	2	2.19	7	1.08	2.4
	MIL	2.19	2	1.95	7	0.25	2.1
	IDLE	3.48 (2)	1	3.90	7	0.33	3.9
NO_x	INT	9.27	2	9.12	7	0.79	9.2
	MIL	9.38	2	9.22	7	0.68	9.3
	IDLE	23.42	2	23.18	7	7.5	23
SMOKE	INT	36.25	2	36.14	7	4.6	36
	MIL	36.42	2	37.66	7	6.1	37

NOTES: (1) Three B runs deleted from hydrocarbon record, incorrect THC caused by leaking glycol coolant from probe.
(2) One NO_x deleted - improper calibration used.

TABLE 5-7 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - TF34-100

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
	IDLE	29.09	1	34.34	5	8.43	32
THC	INT	0.08	1	0.21	5	0.12	0.2
	MIL	0.05	1	0.10	5	0.06	0.1
	IDLE	104.4	1	106.6	5	6.42	106
CO	INT	3.62	1	4.89	5	1.23	4.3
	MIL	2.33	1	2.26	5	0.26	2.3
	IDLE	2.01	1	2.08	5	0.09	2.0
NO_x	INT	7.24	1	7.65	5	0.48	7.5
	MIL	9.75	1	10.34	5	0.59	10
	IDLE	3.67	1	3.63	5	1.30	3.6
SMOKE	INT	2.25	1	0.68	5	0.51	1.4
	MIL	9.79	1	6.13	5	2.56	7.8

TABLE 5-8 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - J57-19W

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
THC	IDLE	79.13	1	75.20	3	13.6	77
	INT	0.15	1	- (1)	-	-	0.2
	MIL	0.09	1	- (1)	-	-	0.1
CO	IDLE	80.82	1	76.44	3	4.20	79
	INT	2.38	1	2.45	3	0.22	2.4
	MIL	1.87	1	1.85	3	0.05	1.9
NO_x	IDLE	2.27	1	2.17	3	0.06	2.2
	INT	9.80	1	8.76	3	0.40	9.5
	MIL	10.80	1	10.26	3	0.47	11
SMOKE	IDLE	7.67	1	10.90	3	0.36	9 (2)
	INT	56.92	1	59.90	3	1.68	58
	MIL	55.83	1	60.73	3	1.50	58

NOTES: (1) THC Data for B tests invalid due to rake probe glycol leak.

(2) The difference between a S/N of 7 and a S/N of 11 is quite small and indistinguishable to the eye of an observer. Therefore, Smoke data was pooled.

TABLE 5-9 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - J57-P21B

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
THC	IDLE	65.22	1	53.44	3	1.65	60
	INT	0.27	1	- (1)	-	-	0.3
	MIL	0.08	1	- (1)	-	-	0.1
CO	IDLE	72.67	1	70.03	3	1.50	72
	INT	3.49	1	2.73	3	0.52	3.2
	MIL	2.02	1	1.91	3	0.31	2.0
NO_x	IDLE	2.41	1	2.23	3	0.04	2.3
	INT	8.26	1	8.32	3	0.52	8.3
	MIL	9.78	1	9.94	3	0.75	9.8
SMOKE	IDLE	8.75	1	12.17	3	1.61	10 (2)
	INT	59.92	1	60.53	3	2.18	60
	MIL	61.63	1	61.00	3	2.60	61

NOTES: (1) THC Data invalid due to glycol leak in Rake Probe.
(2) Difference between S/N of 8 and S/N of 12 is indistinguishable to the observer.

TABLE 5-10 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - J57-P43

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
THC	IDLE	81.13	1	68.35	4	10.4	75
	INT	.09	1	-	-	- ①	0.1
	MIL	.05	1	-	-	- ①	0.1
CO	IDLE	83.03	1	72.35	4	2.76	78
	INT	2.00	1	2.05	4	0.13	2.3
	MIL	1.41	1	1.59	4	0.06	1.5
NO_x	IDLE	2.22	1	2.14	4	0.16	2.2
	INT	10.32	1	9.45	4	0.81	9.9
	MIL	11.26	1	10.75	4	0.80	11
SMOKE	IDLE	7.58	1	8.97	4	1.75	8.3
	INT	55.00	1	58.00	4	3.08	57
	MIL	55.75	1	59.27	4	2.21	58

NOTE: ① THC Data invalid due to glycol leak in probe.

TABLE 5-11 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - J75-19W

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
THC	IDLE	- ①	0	38.16	3	14	38
	INT	-	0	0.31	3	0.10	0.3
	MIL	-	0	0.30	3	0.13	0.3
CO	IDLE	-	0	62.62	3	7.46	62
	INT	-	0	1.86	3	0.21	1.9
	MIL	-	0	1.47	3	6.20	1.5
NO_x	IDLE	-	0	2.55	3	0.06	2.6
	INT	-	0	8.95	3	6.35	9.0
	MIL	-	0	10.48	3	0.34	10
SMOKE	IDLE	-	0	10.67	3	0.58	11
	INT	-	0	51.00	3	1.00	51
	MIL	-	0	51.50	3	2.12	52

NOTE: ① No Category A test this engine model.

TABLE 5-12 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - J75-P17

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
THC	IDLE	94.3 (1)	1	71.9	2	7.0	72
	INT	0.11	1	0.19	2	0.04	0.1
	MIL	0.10	1	0.19	2	0.08	0.1
CO	IDLE	86.4	1	86.0	2	5.3	86
	INT	1.88	1	1.83	2	0.01	1.9
	MIL	1.29	1	1.40	2	0.03	1.3
NO_x	IDLE	2.31	1	2.3	2	.08	2.3
	INT	10.6	1	9.5	2	0.4	10
	MIL	12.6	1	11.2	2	0.3	12
SMOKE	IDLE	10.5	1	14.3	2	1.1	12
	INT	53.3	1	53.5	2	9.2	53
	MIL	53.6	1	49.8	2	1.1	52

NOTE: (1) Category A Idle THC reading contaminated.

TABLE 5-13 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - TF30-P3

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
THC	IDLE	62.11	1	62.87	3	10.9	62
	INT	0.19	1	- (1)	-	-	0.2
	MIL	0.12	1	- (1)	-	-	0.1
CO	IDLE	71.54	1	72.77	3	6.58	72
	INT	2.05	1	2.53	3	0.54	2.3
	MIL	1.25	1	1.52	3	0.52	1.4
NO_x	IDLE	2.42	1	2.15	3	0.29	2.3
	INT	11.63	1	10.44	3	0.69	11
	MIL	14.00	1	13.14	3	1.04	14
SMOKE	IDLE	0.25	1	3.03	3	1.27	0.3 (2)
	INT	28.00	1	36.73	3	0.93	28 (2)
	MIL	29.21	1	33.80	3	3.85	29 (2)

NOTES: (1) THC Data invalid due to glycol leak in rake probe.
(2) Category A and Category B pooled. S/N insignificant. (much less than 25).

TABLE 5-14 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - TF30-P7

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
	IDLE	30.94	1	29.74	3	4.88	30
THC	INT	0.15	1	- ①	-	-	0.2
	MIL	0.09	1	- ①	-	-	0.1
	IDLE	53.36	1	52.58	3	7.81	53
CO	INT	1.11	1	1.24	3	0.08	1.2
	MIL	0.72	1	0.91	3	0.24	0.8
	IDLE	3.19	1	2.77	3	0.24	3.0
NO_x	INT	15.26	1	13.37	3	0.34	14
	MIL	20.95	1	17.82	3	0.75	20
	IDLE	1.03	1	4.57	3	2.98	1 ②
SMOKE	INT	29.17	1	34.40	3	2.71	29 ②
	MIL	27.63	1	33.17	3	2.31	28 ②

NOTES: ① THC Data deleted, data invalid, glycol leak in rake probe.
② S/N of Category A more correct. Rake probe biased toward center of engine where S/N peaks, therefore, Category A S/N selected.

TABLE 5-15 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - TF30-P100

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
THC	IDLE	20.22	1	18.16	4	1.55	19
	INT	0.12	1	- (1)	-	-	0.1
	MIL	0.09	1	- (1)	1	-	0.1
CO	IDLE	48.91	1	48.02	4	3.38	48
	INT	0.65	1	0.80	4	0.22	0.7
	MIL	0.72	1	0.77	4	0.19	0.7
NO_x	IDLE	2.98	1	2.74	4	0.10	2.9
	INT	20.83	1	19.89	4	1.32	20
	MIL	29.64	1	26.49	4	1.79	28
SMOKE	IDLE	1.08	1	4.38	4	0.75	1.0 (2)
	INT	26.00	1	31.6	4	3.07	26 (2)
	MIL	24.50	1	27.42	4	2.87	24 (2)

NOTES: (1) THC deleted, glycol leak in rake probe.
(2) Rake probe biased toward heavy smoke. Category A S/N selected.

TABLE 5-16 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - TF33-P3

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
	IDLE	108.9	1	105.5	4	22.3	107
THC	INT	0.80	1	0.58	4	0.14	0.7
	MIL	0.75	1	0.39	4	0.16	0.6
	IDLE	83.93	1	84.02	4	3.92	84
CO	INT	2.93	1	2.28	4	0.33	2.3 (1)
	MIL	2.24	1	1.66	4	0.14	1.7 (1)
	IDLE	2.20	1	1.84	4	0.11	1.8 (2)
NO_x	INT	8.98	1	8.05	4	0.43	8.5 (3)
	MIL	10.65	1	9.47	4	0.42	10 (3)
	IDLE	10.50	1	15.00	4	3.89	13
SMOKE	INT	54.67	1	56.88	4	5.20	56
	MIL	54.00	1	56.88	4	5.04	56

NOTES: (1) Engine used for A test produced high CO as verified by B test conducted on same engine. A test data ignored and Best Estimate based on B test data.

(2) Category A and Category B data do not agree with acceptable tolerance. Fuel flow for A test higher than maximum value observed in B Tests. Also, EGT higher in A test. Therefore, B value used for Best Estimate.

(3) Difference between Category A and Category B data slightly exceeds allowable tolerance for data pooling - data pooled.

TABLE 5-17 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - TF33-P7

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
	IDLE	86.98	1	67.15	4	11.3	77
THC	INT	0.10	1	- (1)	-	-	0.1
	MIL	0.03	1	- (1)	-	-	0.03
	IDLE	96.44	1	89.67	4	2.89	93
CO	INT	1.29	1	1.24	4	0.22	1.3
	MIL	6.79	1	0.80	4	0.11	0.8
	IDLE	1.69	1	1.82	4	0.11	1.8
NO_x	INT	9.63	1	9.13	4	0.81	9.4
	MIL	11.85	1	11.22	4	1.23	12
	IDLE	6.97	1	9.50	4	4.04	8.2
SMOKE	INT	50.93	1	47.63	4	5.25	49
	MIL	47.98	1	47.00	4	5.23	47

NOTE: (1) Glycol leak in rake probe. Category B data deleted.

TABLE 5-18 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - TF41-A1

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
	IDLE	91.80	1	92.61	5	11.9	92
THC	INT	0.36	1	- (1)	-	-	0.4
	MIL	0.15	1	- (1)	-	-	0.2
	IDLE	118.2	1	119.5	5	2.92	119
CO	INT	3.75	1	3.57	5	0.44	3.7
	MIL	1.87	1	1.81	5	0.16	1.8
	IDLE	1.54	1	1.41	5	.08	1.5
NO_x	INT	12.74	1	12.21	5	.09	12
	MIL	21.55	1	21.31	5	1.18	21
	IDLE	7.50	1	13.00	5	3.76	11 (2)
SMOKE	INT	27.92	1	40.20	5	4.19	35 (3)
	MIL	34.00	1	47.70	5	2.22	42 (3)

NOTES: (1) Rake probe leaked glycol - Category B data deleted.
(2) Low S/N, data pooled.
(3) Data pooled.

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TABLE 5-19 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - F100-PW100

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
THC	IDLE	2.84	2	3.68	5	1.69	3.2
	INT	0.08	3	0.17	5	0.14	0.1
	MIL	0.19	2	0.08	5	0.09	0.1
CO	IDLE	24.04	2	24.39	5	4.21	24
	INT	1.77	3	1.05	5	.09	1.6
	MIL	0.89	2	0.80	5	0.13	0.9
NO_x	IDLE	3.33	2	3.35	5	0.17	3.3
	INT	9.22	3	11.22	5	0.78	9.8
	MIL	26.69	2	26.66	5	2.78	27
SMOKE	IDLE	4.80	1	12.17	4	6.64	5.7
	INT	23.92	1	31.92	4	2.98	28 (1)
	MIL	26.84	1	34.50	4	1.39	31 (1)

NOTE: (1) Data pooled. Although difference between Category B and Category A tests greater than 2 sigma.

TABLE 5-20 COMBINATION OF CATEGORY A AND CATEGORY B TESTS
ENGINE - TF39

		CAT A	NO. OBS	CAT B	NO. OBS	σ_B	BEST ESTIMATE
	IDLE	22.98	4	- (1)	- (1)	3.93	23
THC	INT	0.21	4	-	-	.15	0.2
	MIL	0.18	4	-	-	0.12	0.2
	IDLE	66.73	4	-	-	4.98	67
CO	INT	0.68	4	-	-	.088	0.7
	MIL	0.68	4	-	-	.098	0.7
	IDLE	2.95	4	-	-	0.53	3.0
NO_x	INT	28.36	4	-	-	3.04	28
	MIL	28.52	4	-	-	1.55	28
	IDLE	1.35	2	-	-	.82	1.4
SMOKE	INT	5.64	2	-	-	1.4	5.6
	MIL	5.00	2	-	-	2.4	5.0

NOTE: (1) No B tests - All Category A.

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